



OVER 4,000 PLANETS
HAVE BEEN FOUND ORBITING
DISTANT STARS

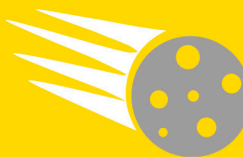


HOW SPACE WORKS

NASA'S
VOYAGER
SPACECRAFT ARE NOW IN
INTERSTELLAR SPACE



THE MOON GETS
3.8 CM FURTHER
FROM EARTH
EACH YEAR



THE FACTS visually explained

THE HUBBLE SPACE
TELESCOPE IS
TRAVELLING AT
28,000 KM/HR



SOME DARK
MATTER
DETECTORS ARE
UNDERGROUND

1.5
KM



AN ASTRONAUT
CAN GROW
3% TALLER
WHILE IN SPACE



THE MILKY WAY
IS ON A COLLISION
COURSE WITH
ANOTHER GALAXY

GOLD
IS MADE IN
SUPERNOVAS



150 BILLION
NEW STARS FORM
EVERY YEAR





HOW SPACE WORKS



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STARS

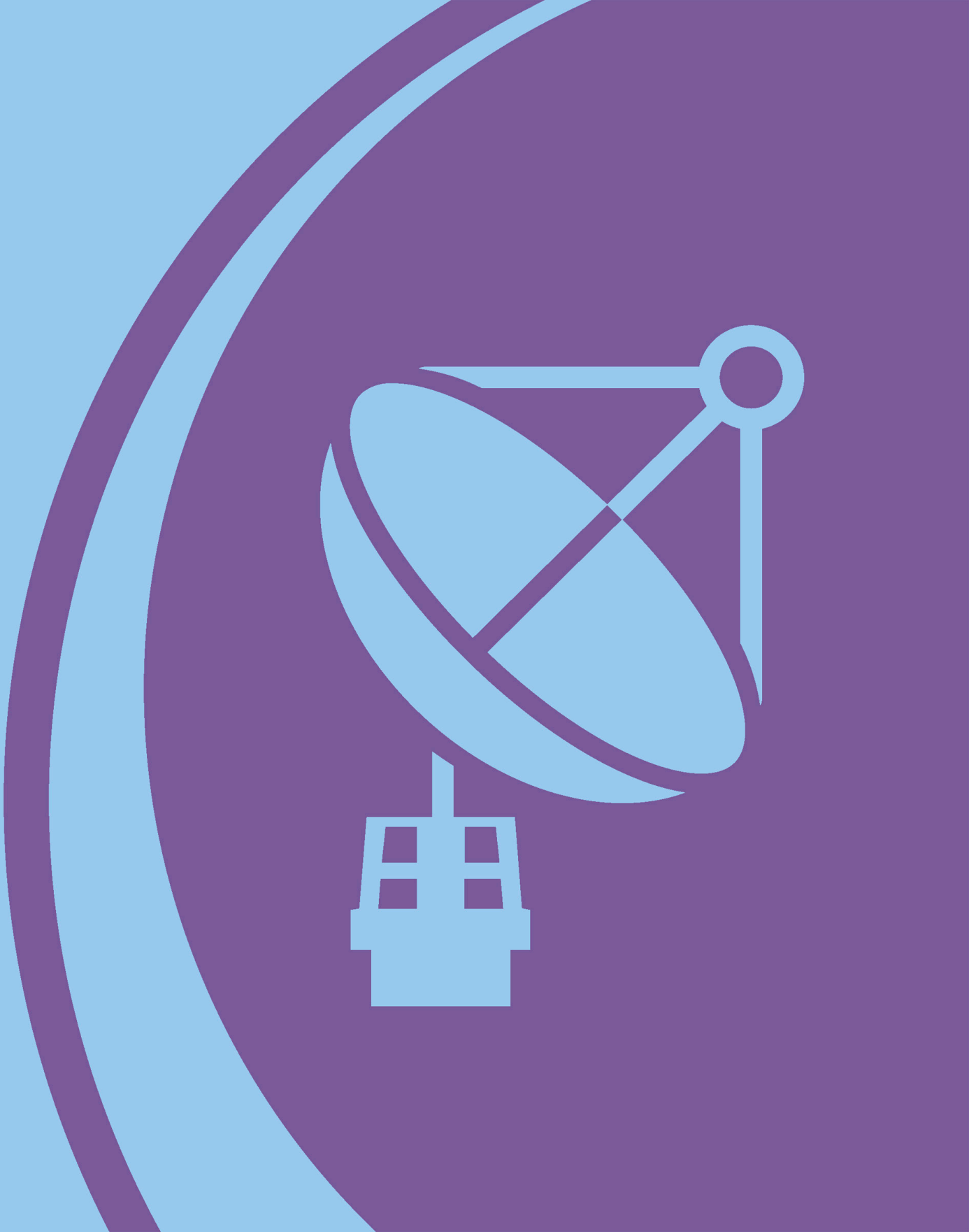
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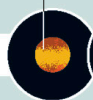


SPACE FROM EARTH

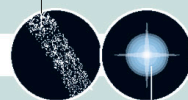
Earth



Venus



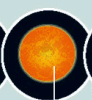
The Oort Cloud



The Moon



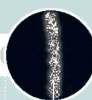
The Sun



Saturn



The Kuiper Belt

Nearest star
(Proxima Centauri)

DISTANCE FROM EARTH

1 MILLION KM

100 MILLION KM

10 BILLION KM

1 TRILLION KM

Earth's diameter is 12,760 km (7,930 miles); the Moon is 384,400 km (238,855 miles) away

The rocky inner planets lie within the Main Belt of asteroids, which is 2.5 times further from the Sun than Earth

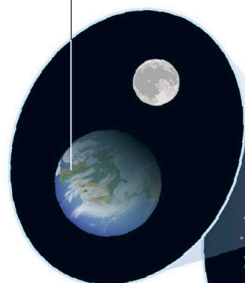
All the planets in the Solar System orbit our local star, the Sun

Beyond the planets is the Kuiper Belt, 15 billion km (9 billion miles) from the Sun

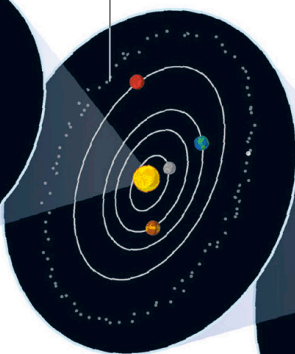
From Earth to the cosmic web

Everything in the Universe, from our planet to clusters of galaxies, is part of a structure. If we could zoom out on the Universe, we'd see an interconnected web of galaxies and gases, called the cosmic web.

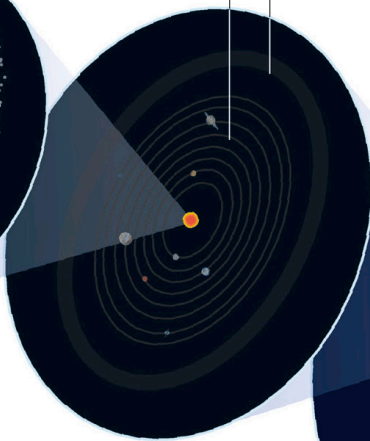
The Solar System is part of the Milky Way galaxy, which includes about 100–400 billion stars



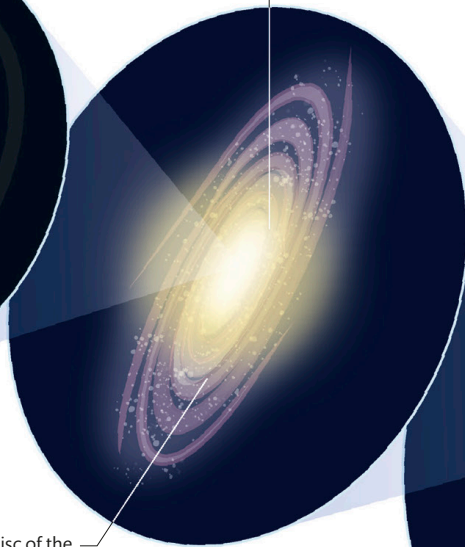
EARTH AND MOON



THE INNER SOLAR SYSTEM



THE SOLAR SYSTEM



THE MILKY WAY

The disc of the Milky Way is 100,000–120,000 light-years across

Structures in the Universe

Everything made of matter in the Universe – including the densest stars, planets, and moons, as well as diffuse gas and dust – can be arranged in a hierarchy of structures, all bound together by gravity. Objects within a structure orbit a centre of mass, usually in the centre of the structure. For example, the planets in the Solar System orbit the central Sun, while everything in our galaxy orbits its centre, which contains a supermassive black hole around 4 million times the mass of the Sun.

Our place in the Universe

The Universe is everything that exists, has existed, or will exist. It comprises all matter and all space, permeated with light and other kinds of radiation. It also includes all time, both past and future.

WHAT SHAPE IS THE UNIVERSE?

Since the Universe does not have a recognizable edge, we cannot say what shape it has. Some cosmological studies suggest it is flat, while other data indicates it might actually be round like a sphere.

1,000 light-year sphere

Sphere contains 90 per cent of naked-eye stars

10^{16} KM

The Andromeda Galaxy

Centre of the Milky Way

10^{18} KM

The Virgo Cluster

10^{20} KM

Nearest quasar

10^{22} KM

Edge of observable Universe



Cosmic distances

Distances in the Universe cannot be represented with a simple linear scale. On this chart, each division represents a distance 10 times greater than the previous division.

THE AGE OF THE UNIVERSE IS 13.8 BILLION YEARS



Size and distance

Outside the Solar System, distances become so vast that new units are needed to measure them. One of these units is the light-year, the distance that photons, particles of light or other electromagnetic radiation, cover in one year. A light-year is about 9.5 trillion km (5.9 trillion miles). The part of the Universe we can see, called the observable Universe, is limited by this distance, since light has had only the time since the Big Bang to reach us. We cannot see anything beyond this limit, known as the cosmic light horizon. The size of the whole Universe is unknown. One possibility is that it is infinite, meaning it has no edge.

The Milky Way is one of a cluster of galaxies called the Local Group

All the galaxy clusters in a supercluster are in orbit around the centre of the cluster

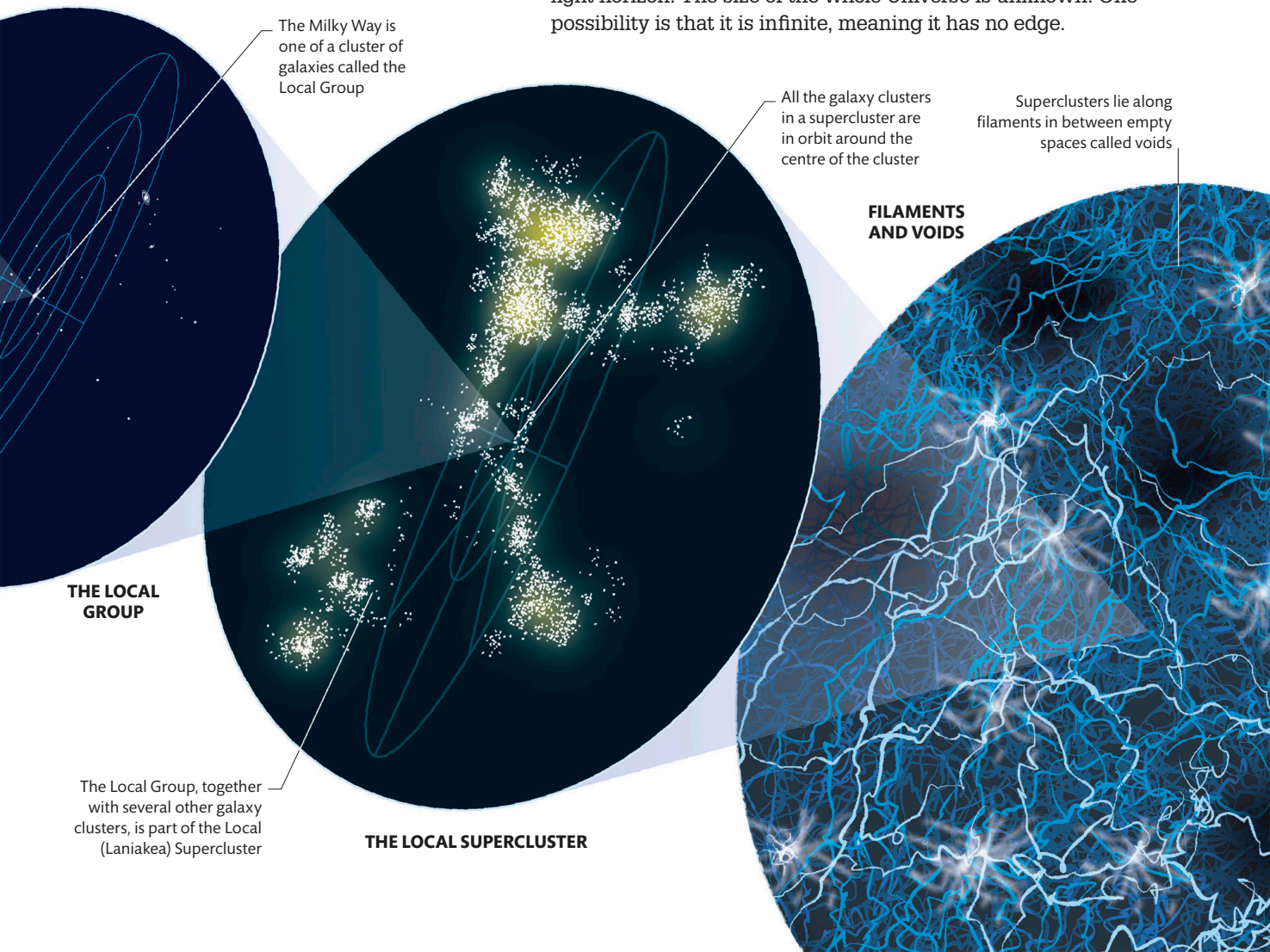
Superclusters lie along filaments in between empty spaces called voids

FILAMENTS AND VOIDS

THE LOCAL GROUP

The Local Group, together with several other galaxy clusters, is part of the Local (Laniakea) Supercluster

THE LOCAL SUPERCLUSTER

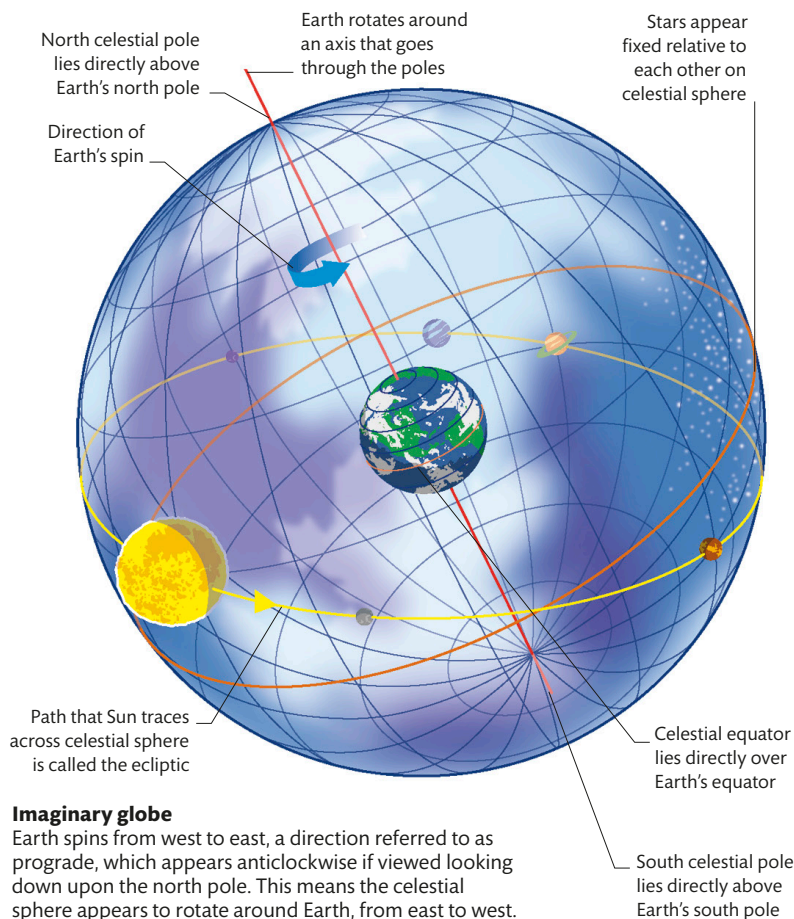


Looking into space

For most of human history, the Sun was thought to orbit Earth because of the way it moves in the sky. Now we know that Earth orbits the Sun and spins on an axis too. Together, these motions create the apparent movement of the night sky around us.

The celestial sphere

The planets that are visible to the naked eye are much closer than the stars in the night sky. However, for the purposes of identifying the position of each celestial object, astronomers imagine everything, including stars, planets, and the Moon, as points on an imaginary sphere with an arbitrary radius around Earth. This is called the celestial sphere.



Imaginary globe

Earth spins from west to east, a direction referred to as prograde, which appears anticlockwise if viewed looking down upon the north pole. This means the celestial sphere appears to rotate around Earth, from east to west.

HOW FAR AWAY IS THE SUN?

Earth's elliptical orbit means that the distance between it and the Sun varies, but the average distance is 151 million km (93 million miles).

How the sky changes

Over a day, the celestial sphere appears to rotate around Earth. This means that the stars, although fixed relative to each other, trace a circular path across the sky. Except for stars near the poles, most stars appear to rise and set. As Earth orbits the Sun, the stars that are visible at night vary through the year depending on Earth's position. This means that every night, the appearance of the night sky gradually shifts position. From one day to the next, if you were to look at the sky at exactly the same time, the stars would have shifted their positions by about one degree.

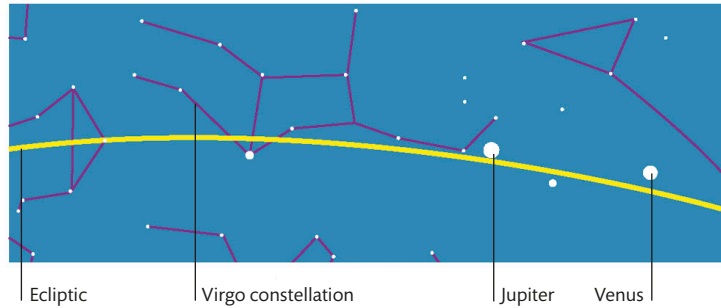
POSITION OF OBSERVER IN AUGUST





THE ECLIPTIC

Over a year, as Earth orbits the Sun, our star seems to trace a line across the celestial sphere. This path, the plane of Earth's orbit, is called the ecliptic. The other planets orbit more or less in the same plane as Earth and always appear near this line. The Moon orbits at a shallow angle in relation to the ecliptic, and eclipses only occur when the Moon travels through it.



Parallax

If you look at something with one eye and then through the other, it will appear to shift slightly. In the same way, objects in the sky appear in different positions depending on where Earth is in its orbit around the Sun. This is called parallax. The closer an object is to Earth, the further it appears to move and the greater its parallax angle. This means that parallax measurements can be used to calculate distances to stars.

Angle of Pleiades star cluster as seen by observer on Earth is more acute in August

Direction of Earth's orbit around Sun

POSITION OF OBSERVER IN FEBRUARY

SEEN AGAINST THESE OBJECTS IN FEBRUARY

SEEN AGAINST THESE OBJECTS IN AUGUST

PLEIADES STAR CLUSTER

Pleiades star cluster passes high overhead in northern hemisphere in February

PARALLAX ANGLE

Position of north celestial pole

Each trail is the path of a circumpolar star rotating around the north celestial pole

Circumpolar star trails

Some stars are visible all year round; instead of rising and setting, these stars circle around the poles. In a long-exposure photograph, their movement creates distinctive circular star trails.

AFTER THE SUN, PROXIMA CENTAURI IS THE CLOSEST STAR TO EARTH, SITUATED APPROXIMATELY 4.22 LIGHT-YEARS AWAY

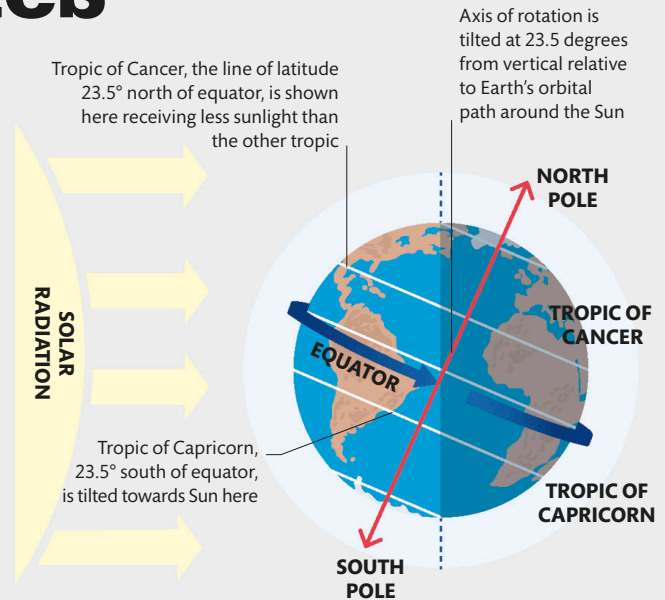


Celestial cycles

To us on Earth, celestial events occur in cycles determined by the movements of Earth, the Sun, and the Moon. These cycles give rise to units of measurement for time, such as days and years, and to seasons. Related cycles are responsible for spectacular lunar and solar eclipses.

Why we have seasons

Earth orbits the Sun while spinning on its axis, which runs between the north and south poles. However, the axis of Earth's rotation is tilted about 23.5 degrees from the vertical in relation to the plane of the orbit around the Sun. This tilt means that there are certain points in its orbit where Earth's north pole is pointing towards the Sun, and others where it points away. This tilt also means that the amount of sunlight Earth's north and south hemispheres receive changes over a year. The change in the amount of daylight in each hemisphere is the reason Earth experiences seasons.



The Earth's tilt

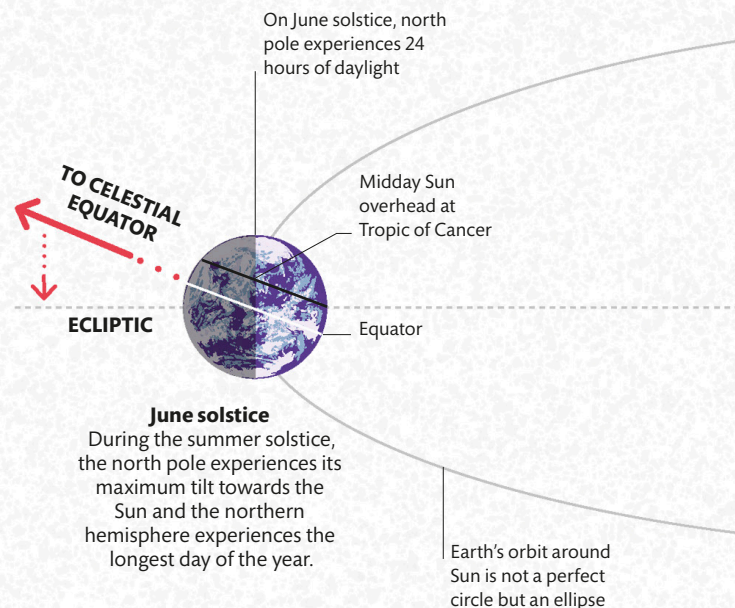
In the hemisphere that is tilted away from the Sun, solar radiation is spread out over a greater area of Earth's surface. This heats the surface less intensely, making it cooler than the other hemisphere.

Days and years

There are two ways of measuring days and years. A solar year, or a tropical year, is the time it takes Earth to return to the same angle with respect to the Sun. A sidereal year is measured using Earth's position relative to the fixed stars. The difference between the two is about 20 minutes. In the same way, a sidereal day is measured by Earth's rotation compared to the fixed stars, while a solar day is the time it takes for the Sun to return to the same position in the sky. The difference between the two is four minutes, because of the distance that Earth has moved in its orbit around the Sun during that time.

Solstices and equinoxes

At the solstices, one hemisphere experiences its longest day, followed by the other hemisphere six months later. At the equinoxes, night and day are both exactly 12 hours long everywhere on Earth.





WHY DOES EARTH TILT?

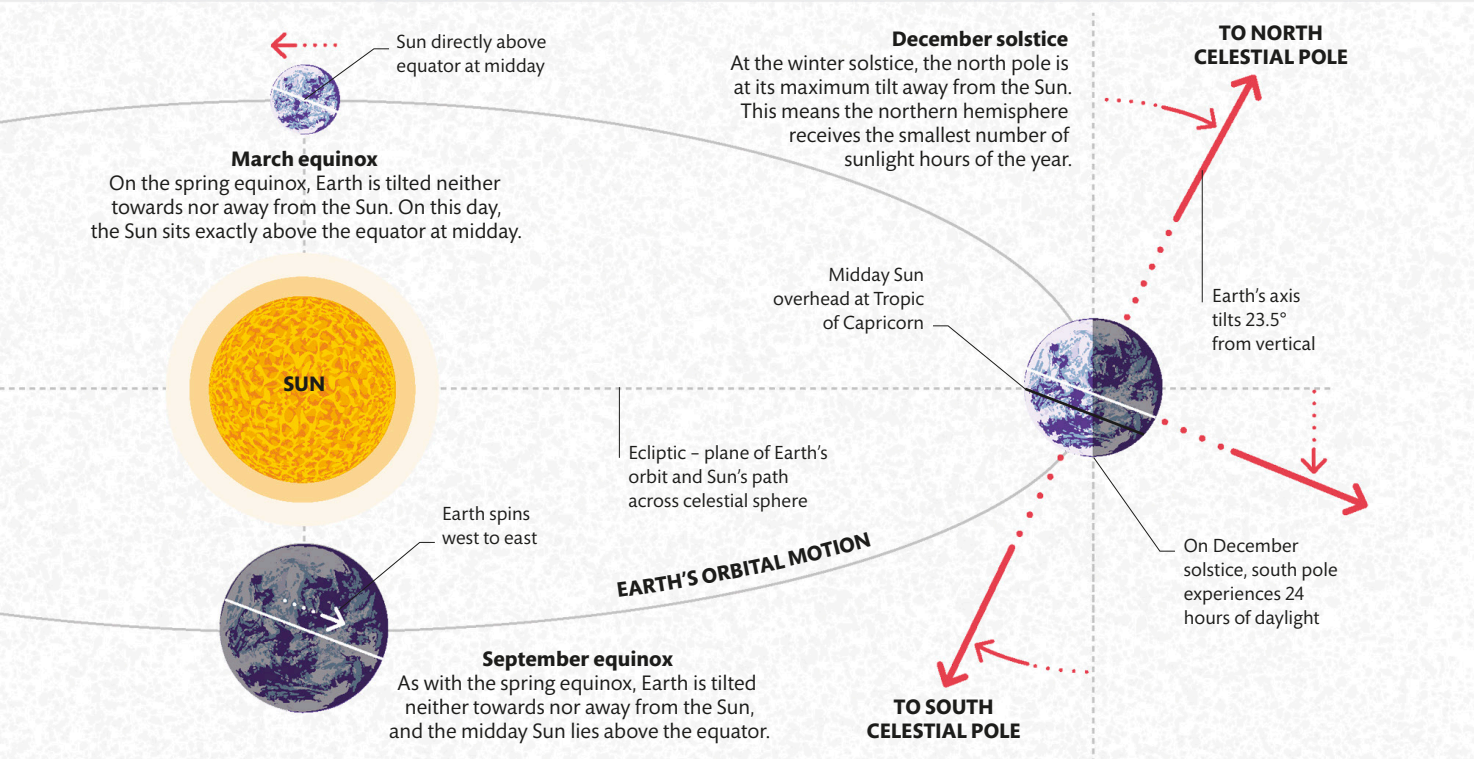
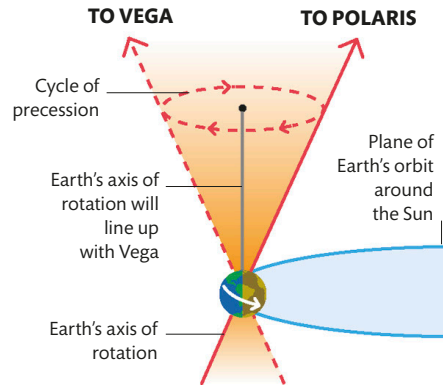
Four billion years ago, when the planets of our Solar System were forming, Earth suffered a series of collisions with other planet-sized objects. The last of these, thought to have been with a Mars-sized planet, threw Earth's spin into a tilt.

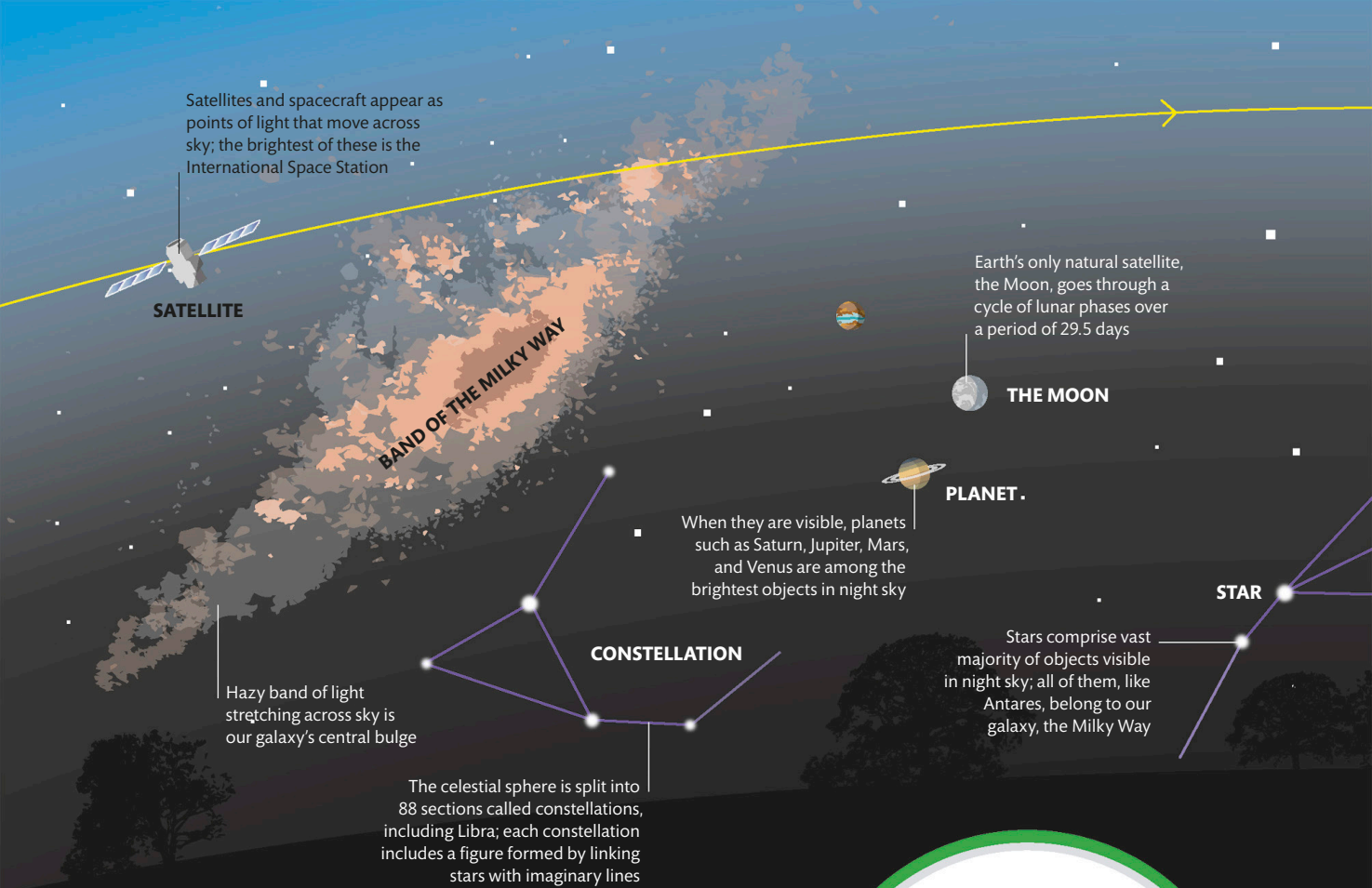


EARTH IS CLOSEST TO THE SUN IN JANUARY, DURING THE NORTHERN-HEMISPHERE WINTER

PRECESSION

Due to gravity, Earth's axis of rotation is moving around, like a spinning top, in a cone-shaped motion called precession. It takes 25,772 years to complete one cycle of precession. This means that the north star, Polaris, will not always be situated almost directly above the north pole as it is now. Eventually the star Vega will replace Polaris as the north star.





What can we see with the naked eye?

The night sky is an endless source of wonder, and it only requires a pair of eyes to see a variety of different objects. Over the course of just an hour on any given night, you will be able to see countless stars, at least one meteor, a satellite, and maybe even a planet or two. Away from light pollution, which makes the features of the night sky difficult to make out, the glow from our own Milky Way galaxy's core of stars and dust shines like a faint stripe across the sky.

HOW MANY STARS ARE VISIBLE WITH THE NAKED EYE?

With perfect conditions and excellent eyesight, over 9,000 stars are visible to the naked eye, although at any given location only half of these can be seen at once.

Objects in the sky

During the day, the light from the Sun dominates the sky so that nothing else, except the Moon, is visible. But at night, as we turn our backs on the Sun, the night sky reveals a wide variety of celestial objects, some visible to the naked eye and some revealed using magnification.



METEOR

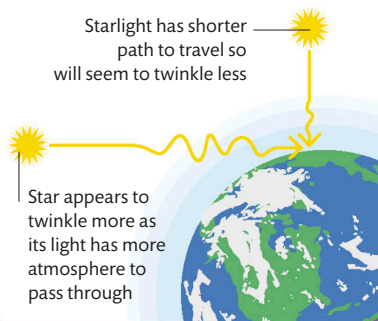
Meteors are bits of rock and dust, broken off from comets and asteroids, which enter atmosphere at high speeds and burn up

Visible with the naked eye

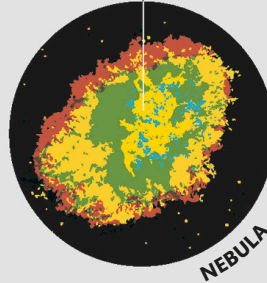
All of the celestial objects shown here against the night sky are visible with the naked eye on a clear night. The brightest object by far is a full Moon.

WHY STARS TWINKLE

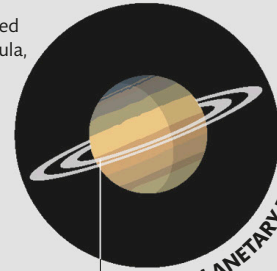
Stars twinkle because of turbulence in Earth's atmosphere. Changes in density and temperature can cause starlight to change direction slightly. This effect is more visible in stars than in planets, because their light appears to come from a single point, known as a point source. It is also more prominent in stars lower towards the horizon, because the light has to travel through more of the atmosphere.



Binoculars are needed to see the Crab Nebula, a remnant from an exploding star

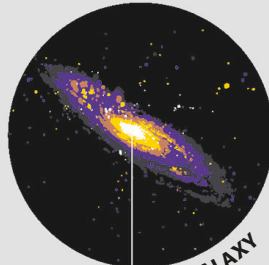


NEBULA



PLANETARY RINGS

The rings around Saturn are only visible using high-power binoculars or a small telescope



GALAXY

The Andromeda Galaxy, 2.5 million light-years away, is the most distant object visible with the naked eye, but it can be seen in much greater detail through a telescope

Visible using binoculars and telescopes

Binoculars are portable and easy to use, and are a good way to see more objects and finer detail in the night sky. Using the greater magnification offered by a telescope opens up even more of the night sky to an observer.

What can we see with magnification?

There are plenty of amazing celestial objects to see with the naked eye, but equipment that magnifies these distant objects reveals a new level of detail. Through binoculars the colour of planets, the details of nebulae, the craters on the Moon's surface, and star clusters can all be seen. With the smallest telescopes, details like the rings around Saturn and the shapes of nearby galaxies start to appear. Bigger telescopes can peer beyond our galaxy.



**NEARLY EVERY STAR YOU CAN SEE
WITH THE NAKED EYE IS BIGGER
AND BRIGHTER THAN THE SUN**

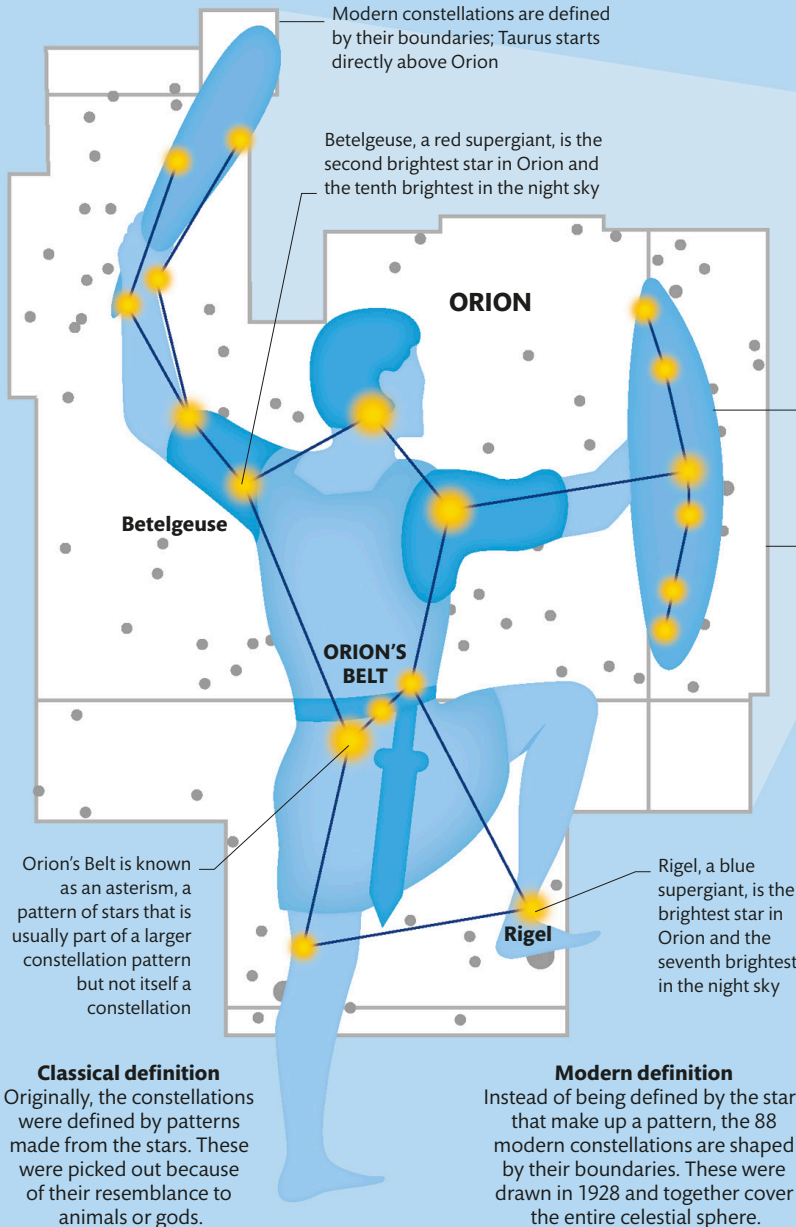
Constellations

In astronomy, the night sky is split into sections called constellations. Historically, these were imaginary patterns of stars, but in the early 20th century they were redefined as areas of sky. Although they might look like a group, the stars in a constellation are not necessarily close to each other in space.

The 88 constellations interlock to fill the entire sky



CELESTIAL SPHERE



Modern constellations are defined by their boundaries; Taurus starts directly above Orion

Betelgeuse, a red supergiant, is the second brightest star in Orion and the tenth brightest in the night sky

ORION

Betelgeuse

ORION'S BELT

Rigel

The pattern created by imaginary lines drawn between the stars resembles the classical figure of Orion

The boundaries of modern constellations are straight lines, either horizontal or vertical

Orion's Belt is known as an asterism, a pattern of stars that is usually part of a larger constellation pattern but not itself a constellation

Rigel, a blue supergiant, is the brightest star in Orion and the seventh brightest in the night sky

Classical definition

Originally, the constellations were defined by patterns made from the stars. These were picked out because of their resemblance to animals or gods.

Modern definition

Instead of being defined by the stars that make up a pattern, the 88 modern constellations are shaped by their boundaries. These were drawn in 1928 and together cover the entire celestial sphere.

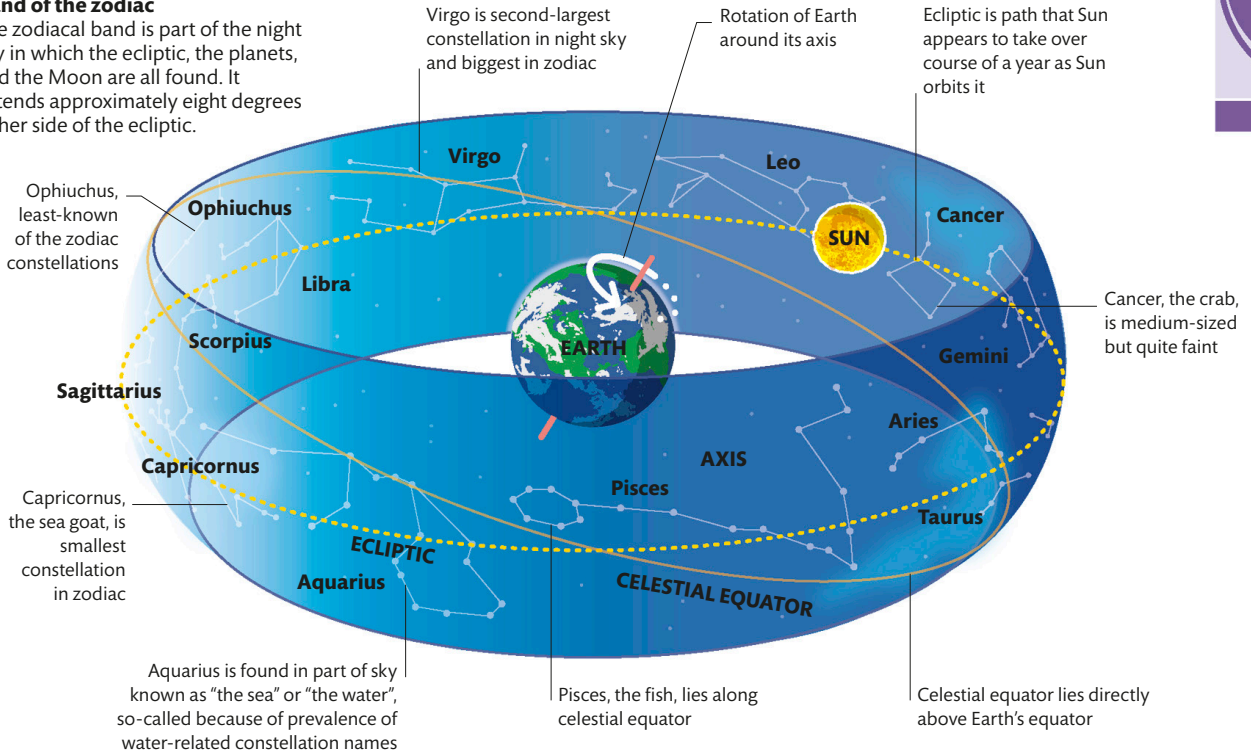
Patterns in the sky

Constellations are a way of grouping stars together. There are 88 official constellations recognized by the International Astronomical Union. These are often depicted by drawing lines between stars to mark out a pattern. However, constellations are actually defined by their boundaries, not by the patterns the stars create in the sky. Together, the 88 constellations cover the entire celestial sphere (see p.12). Every star that falls within a boundary is part of that constellation, even if it is not one of the main stars creating the pattern.



Band of the zodiac

The zodiacal band is part of the night sky in which the ecliptic, the planets, and the Moon are all found. It extends approximately eight degrees either side of the ecliptic.



The zodiac

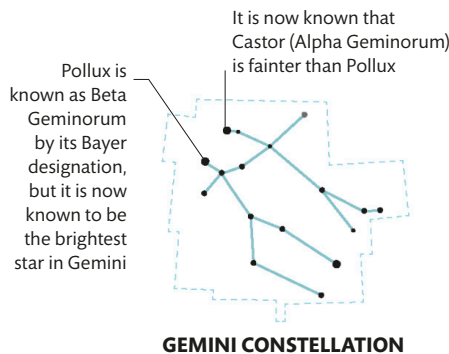
The 13 constellations that intersect with the path the Sun appears to trace in the sky over the course of a year are known as the constellations of the zodiac. They include the 12 “star-sign” constellations and a thirteenth, Ophiuchus, which is situated between Sagittarius and Scorpius. The zodiac comprises around one-sixth of the surface area of the celestial sphere.

THE CONSTELLATION
HYDRA IS SO LARGE
THAT IT COVERS 3 PER
CENT OF THE ENTIRE
NIGHT SKY



BAYER DESIGNATIONS

A system of naming stars invented by German astronomer Johann Bayer in 1603 is still used today. A star is named by a Greek letter followed by the constellation name it falls within. These letters were assigned in order of brightness with the 17th-century equipment available to Bayer.



DO THE CONSTELLATIONS CHANGE OVER TIME?

In around 50,000 years, some constellations will bear no resemblance to their current patterns. The further a star is away from Earth, the less it will change position.

Mapping the sky

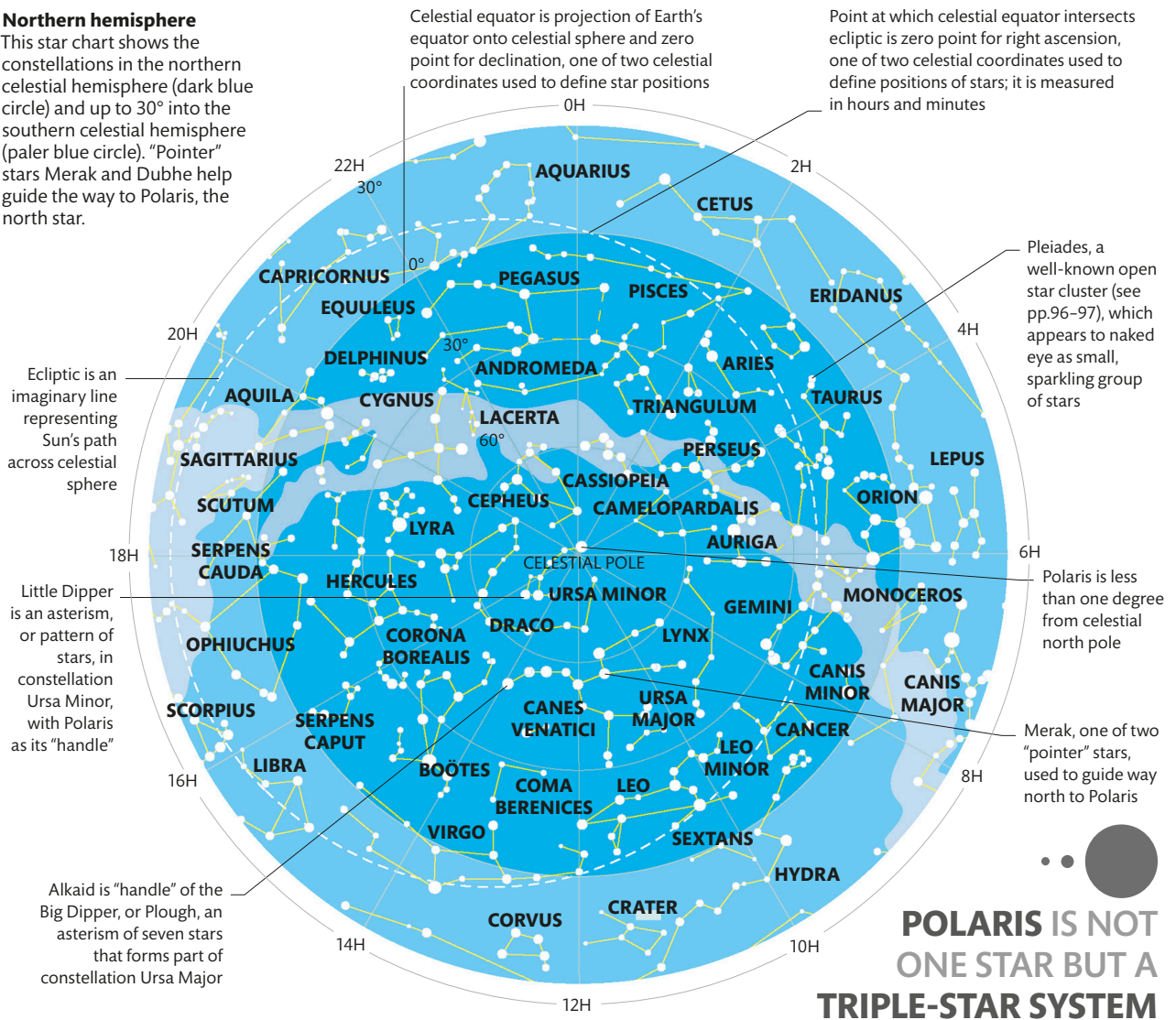
A star chart is a flattened representation of part of the celestial sphere (see p.12). A typical chart shows the names and positions of stars and constellations and often other objects, such as clusters and nebulae. Stars are usually represented by dots, with large dots for bright stars and small dots for faint stars.

How to navigate the skies

As your view of the sky depends on the hemisphere you are in and your latitude, it is important to find a chart that corresponds to your location. When looking at the night sky, the best way to orientate yourself is often to find a few bright stars and constellations, and then use them as pointers to other stars. A useful tool for orientation is a planisphere, which consists of a circular chart with an oval window that can be rotated to show how the sky looks at a given date and time.

Northern hemisphere

This star chart shows the constellations in the northern celestial hemisphere (dark blue circle) and up to 30° into the southern celestial hemisphere (paler blue circle). "Pointer" stars Merak and Dubhe help guide the way to Polaris, the north star.





HOW NEAR ARE THE CLOSEST STARS?

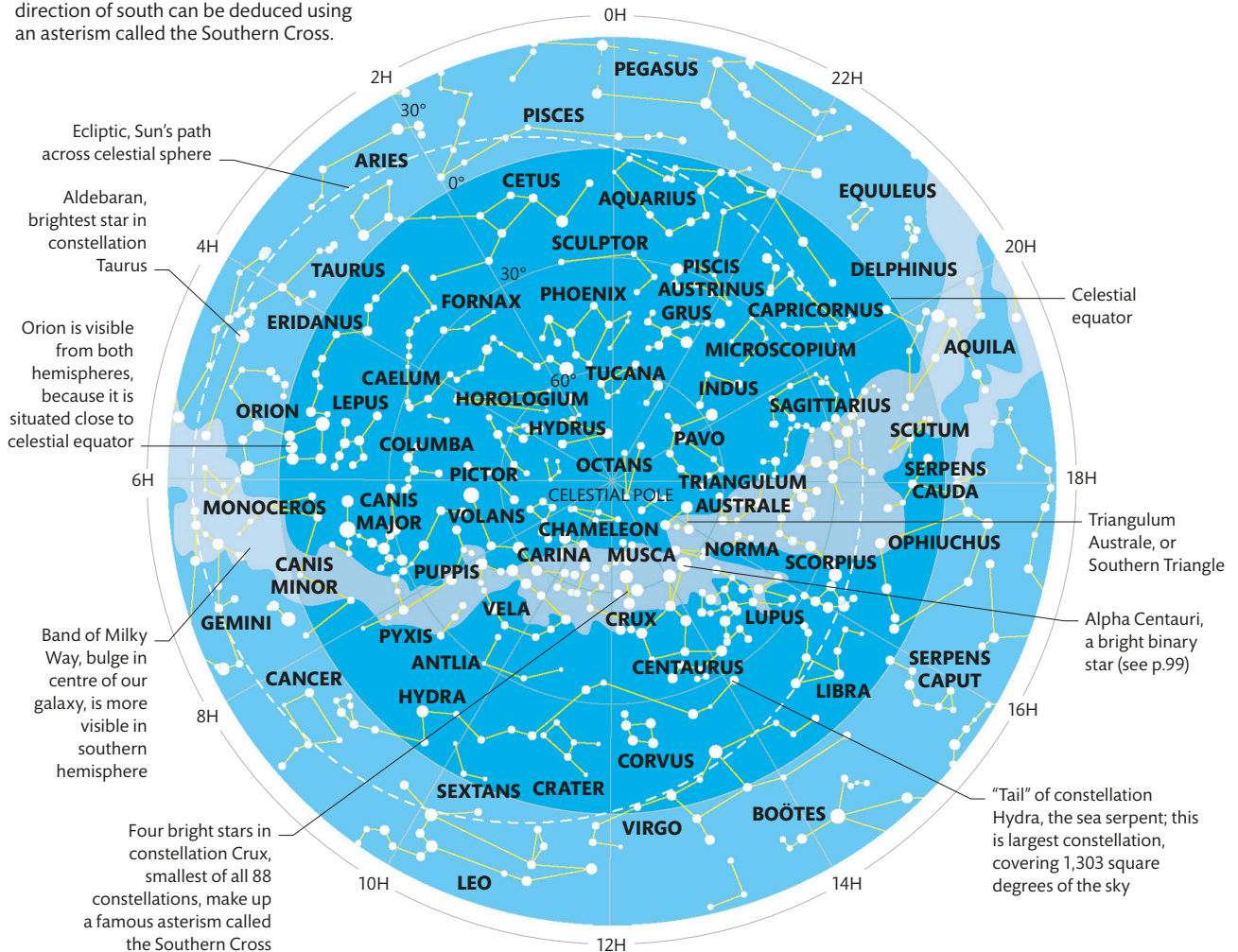
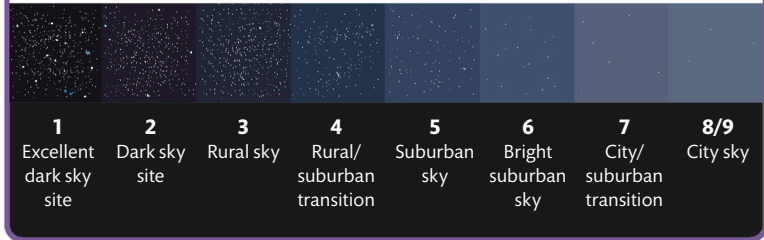
Proxima Centauri is the closest star to Earth, situated around 4.22 light-years away. The closest star system to us is Alpha Centauri, which lies 4.37 light-years away.

Southern hemisphere

Unlike in the northern hemisphere, in the southern hemisphere there is no bright star at the south celestial pole, but the direction of south can be deduced using an asterism called the Southern Cross.

THE BORTLE SCALE

Light from artificial sources, especially in urban environments, obscures the view of the night sky, meaning that only the brightest objects can be seen. The greater the light pollution, the fewer stars visible in that area. The Bortle scale was created in 2001 to evaluate light pollution in given locations. It ranges from 1–9, with 1 representing the clearest skies.



Telescopes

It is possible to view many objects in the night sky with the naked eye. However, to study these in more detail, and to view fainter objects, requires a piece of equipment capable of collecting and focusing light to produce a magnified image. Telescopes do this in two ways, by using either mirrors or lenses.

THE REFLECTING TELESCOPE WAS INVENTED BY SIR ISAAC NEWTON IN 1668

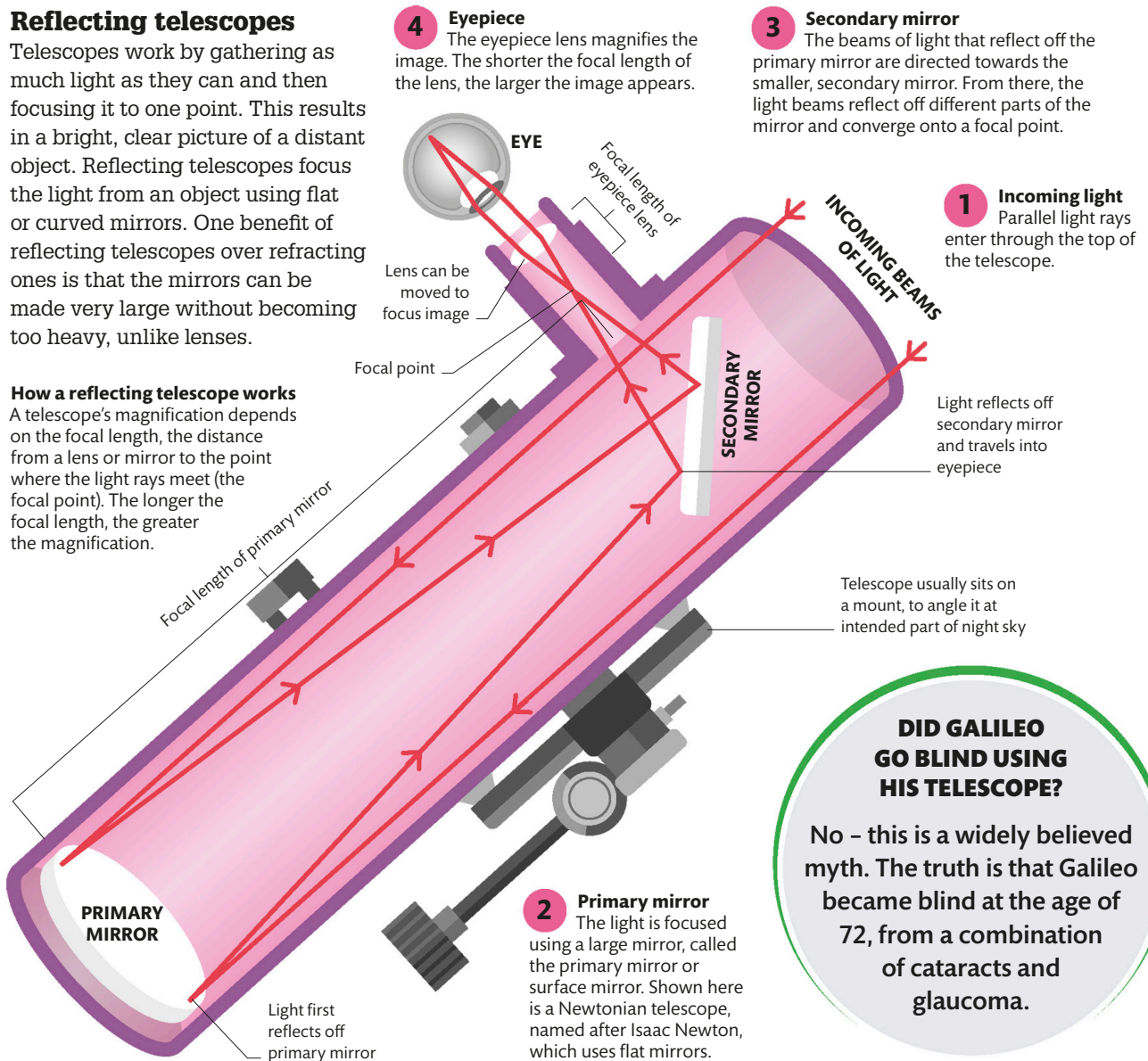


Reflecting telescopes

Telescopes work by gathering as much light as they can and then focusing it to one point. This results in a bright, clear picture of a distant object. Reflecting telescopes focus the light from an object using flat or curved mirrors. One benefit of reflecting telescopes over refracting ones is that the mirrors can be made very large without becoming too heavy, unlike lenses.

How a reflecting telescope works

A telescope's magnification depends on the focal length, the distance from a lens or mirror to the point where the light rays meet (the focal point). The longer the focal length, the greater the magnification.



DID GALILEO GO BLIND USING HIS TELESCOPE?

No – this is a widely believed myth. The truth is that Galileo became blind at the age of 72, from a combination of cataracts and glaucoma.

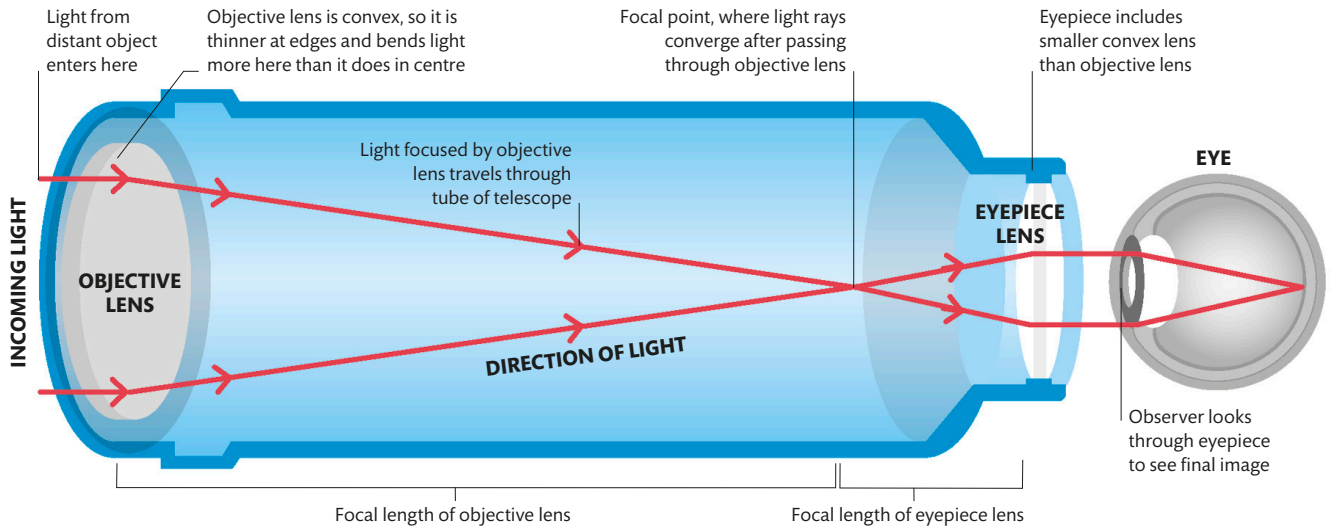


Refracting telescopes

Refracting telescopes use lenses to produce a magnified image. While these telescopes are more robust and need less maintenance than reflecting telescopes, the lenses have to be very large to see distant objects, which makes them heavy. This also means that any slight imperfection in the lens will have a big impact on the final image. They also suffer from defects like chromatic aberration, where colours are bent to different extents by the lens due to their different wavelengths.

How a refracting telescope works

A simple refracting telescope can be created using two lenses, both convex. The biggest lens is an objective lens, which focuses light from a distant object.



1 Objective lens

Parallel light rays enter the telescope and hit the objective lens. The lens is convex, which means it focuses the light to a point. The bigger the objective lens, the more the telescope is able to magnify the object.

2 Focal point

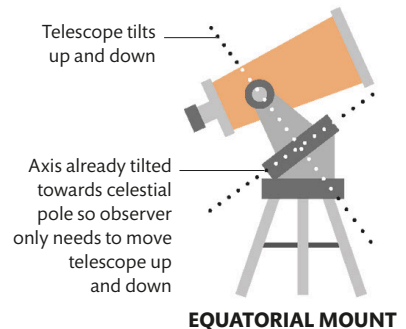
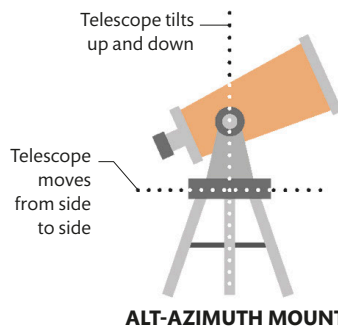
This is the point where the focused rays of light come together after passing through the objective lens. Here, an image is at its sharpest. After this point, the light disperses again.

3 Eyepiece

A small lens is used to refract the light that has passed through the objective lens. Light rays that pass through the lens exit in parallel, creating a virtual image in the eyepiece.

TELESCOPE MOUNTS

Telescopes are usually placed on mounts to keep them steady and help the viewer find objects in the sky. There are two main types of telescope mount: alt-azimuth and equatorial. An alt-azimuth mount uses two axes of rotation, both of which need to be moved to track a celestial object. An equatorial mount also uses two axes but has one axis aligned so it points to the celestial pole (see pp.12-13).



Giant telescopes

Housed in observatories, many huge telescopes are optical instruments, collecting light from near the edge of the observable Universe (see pp.160–61). Other telescopes study different parts of the electromagnetic spectrum.

Giant optical telescopes

On Earth, most big telescopes are built at the highest altitudes in dry places like the Atacama Desert. This is because the height and lack of moisture reduce the amount of atmospheric turbulence that light has to pass through before reaching the telescope. The most distant peering can be undertaken by space telescopes (see pp.186–87), where the atmosphere is not a problem. On Earth, adaptive optics technology can help to compensate for the effects of distortion caused by the atmosphere.

Adaptive optics

Laser beams stimulate sodium atoms in the mesosphere, to create artificial “guide” stars. These are used to determine the distortion caused by the atmosphere. The segmented primary mirror then changes shape to correct the distortion and bring the telescope’s target object into focus.

Light reaches Nasmyth focus, mounted on steel platform, which also houses telescope’s eyepiece

2 Primary mirror

Light first hits this 36-segment primary mirror, which can change its shape up to 2,000 times a second, to cancel out distortions from the atmosphere.

1 Incoming starlight

Light from a distant object enters the telescope in a straight line and travels to the primary mirror.

3 Secondary mirror

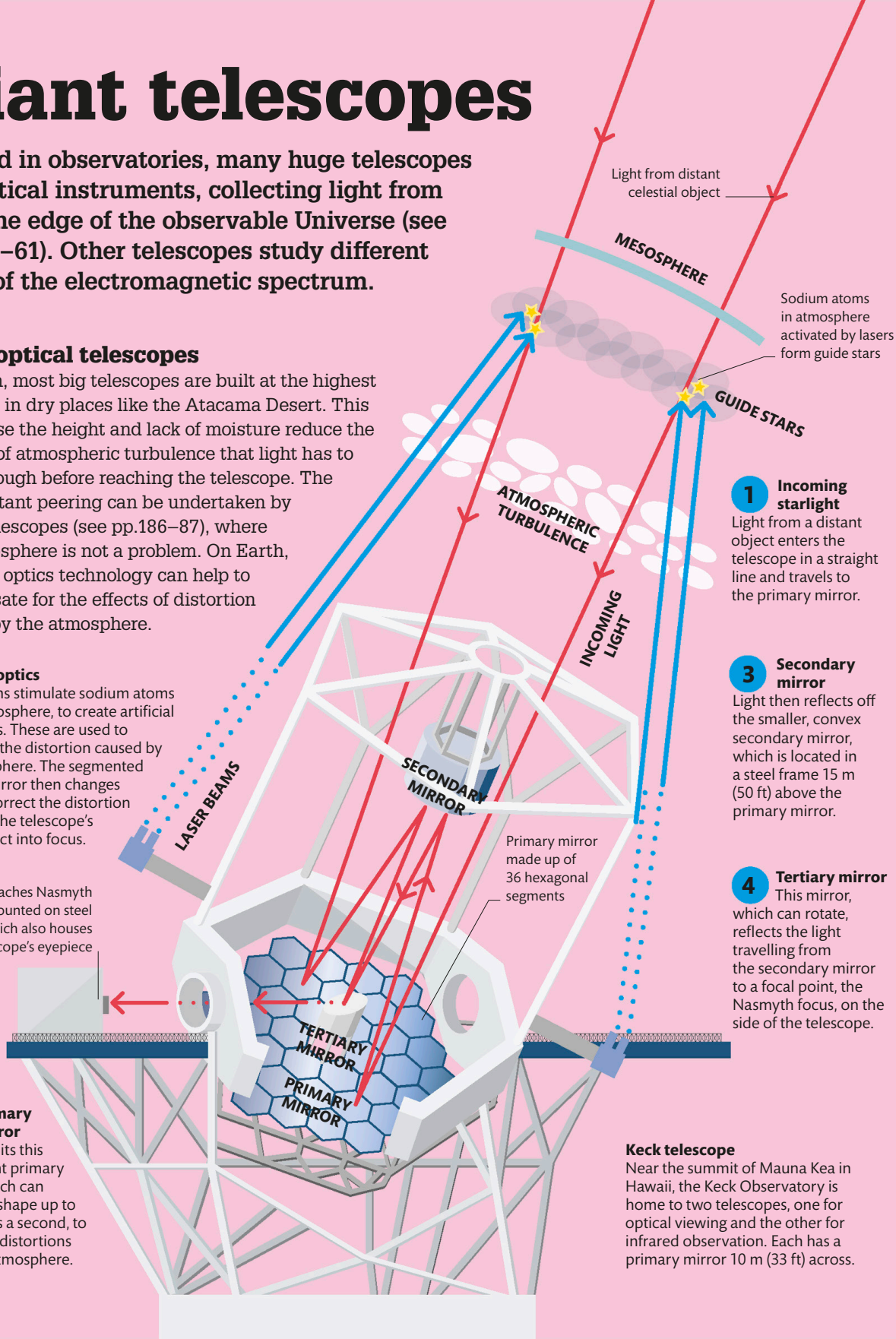
Light then reflects off the smaller, convex secondary mirror, which is located in a steel frame 15 m (50 ft) above the primary mirror.

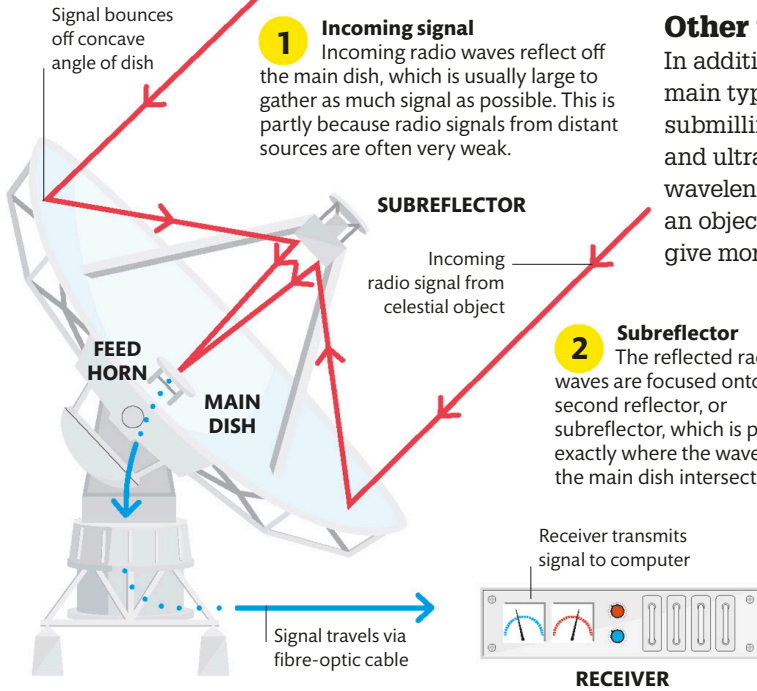
4 Tertiary mirror

This mirror, which can rotate, reflects the light travelling from the secondary mirror to a focal point, the Nasmyth focus, on the side of the telescope.

Keck telescope

Near the summit of Mauna Kea in Hawaii, the Keck Observatory is home to two telescopes, one for optical viewing and the other for infrared observation. Each has a primary mirror 10 m (33 ft) across.



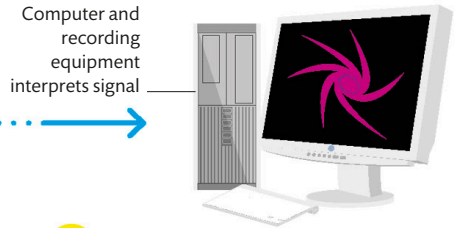


1 Incoming signal
Incoming radio waves reflect off the main dish, which is usually large to gather as much signal as possible. This is partly because radio signals from distant sources are often very weak.

2 Subreflector
The reflected radio waves are focused onto a second reflector, or subreflector, which is placed exactly where the waves from the main dish intersect.

How a radio telescope works

Radio telescopes are specifically designed to receive long-wavelength radio waves from space. They typically feature a large parabolic dish that reflects the radio waves to a subreflector and on to a receiver.



3 Feed horn
After bouncing off the subreflector, the signal travels through the feed horn in the centre of the dish to the receiver.

4 Receiver
The receiver features an amplifier, which increases the signal strength. Then the signal travels to a computer.

5 Computer
Signals are stored on a computer and are either processed there or sent on for analysis using sophisticated software.

WHAT IS THE WORLD'S HIGHEST OBSERVATORY?

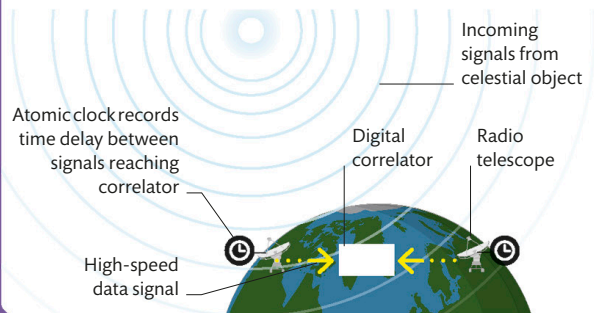
The University of Tokyo's Atacama observatory, on the summit of Cerro Chajnantor in Chile, is located at a height of 5,640 m (18,500 ft).

THE KECK TELESCOPE
CAPTURED THE FIRST
IMAGE OF AN EXTRASOLAR
PLANETARY SYSTEM IN 2008



ASTRONOMICAL INTERFEROMETRY

An astronomical interferometer combines the light or radio signals from two or more telescopes. This allows astronomers to examine a celestial object in more detail, as though it is being observed using mirrors or antennas measuring hundreds of metres in diameter. It is achieved by setting up arrays of telescopes that observe an object at the same time. A digital correlator processes the signals and allows for the time lag between the telescopes.

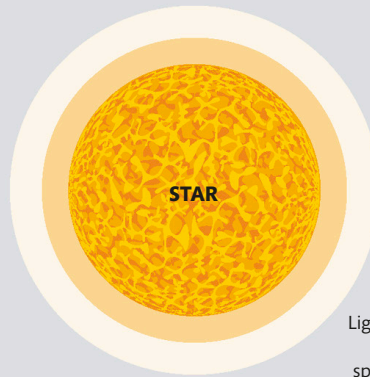


Spectroscopy

Astronomers can identify what elements or molecules are present in a star or other celestial object, by studying the light that it emits or absorbs. This is undertaken using a technique called spectroscopy, which splits electromagnetic radiation into separate wavelengths.

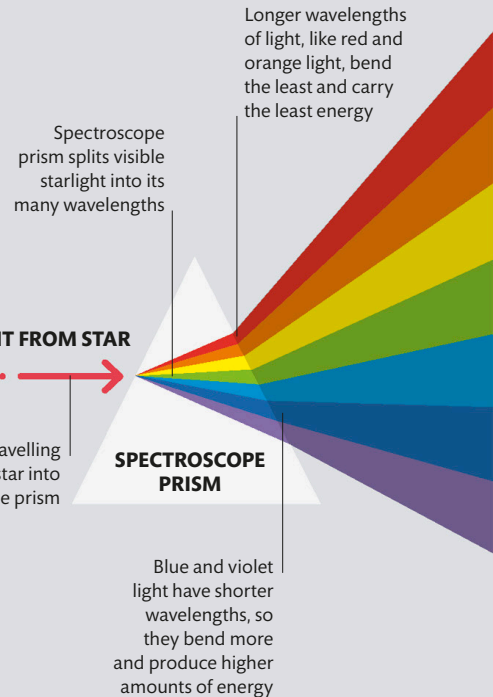
What stars are made of

Visible light is one part of a spectrum of electromagnetic radiation (see pp.152–53). Elements emit different wavelengths of light, depending on their inherent energy levels. Because we know the wavelengths that correspond to particular elements, we can use instruments to analyse light to find out what stars and other celestial objects, including nebulae (see pp.94–95) and black holes, are made of. One such instrument is a spectroscope, which focuses a beam of light at a prism to separate it into its constituent wavelengths.



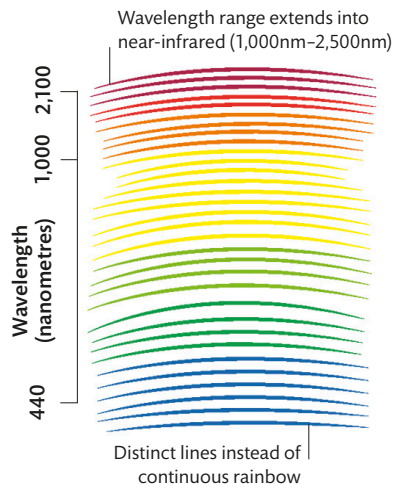
How a spectroscope works

Starlight travels into a prism, a transparent optical device that bends light. As light enters the prism, it slows down, but each wavelength, which corresponds to a different colour, slows down to a different extent. The wavelengths exit the prism at different points, producing a rainbow of colours.



SPECTROGRAPHS

Spectrographs are more sophisticated instruments than spectroscopes. They use thin slits, mirrors, and a diffraction grating – an opaque screen scored with many transparent parallel lines – to separate the light at a more detailed level. Instead of a rainbow, the output is a spectrum in which the light is separated into individual wavelengths. Increasingly, astronomers use a technique called multi-object spectroscopy, in which they study the spectra from more than one celestial object within the field of view of the instrument at the same time.

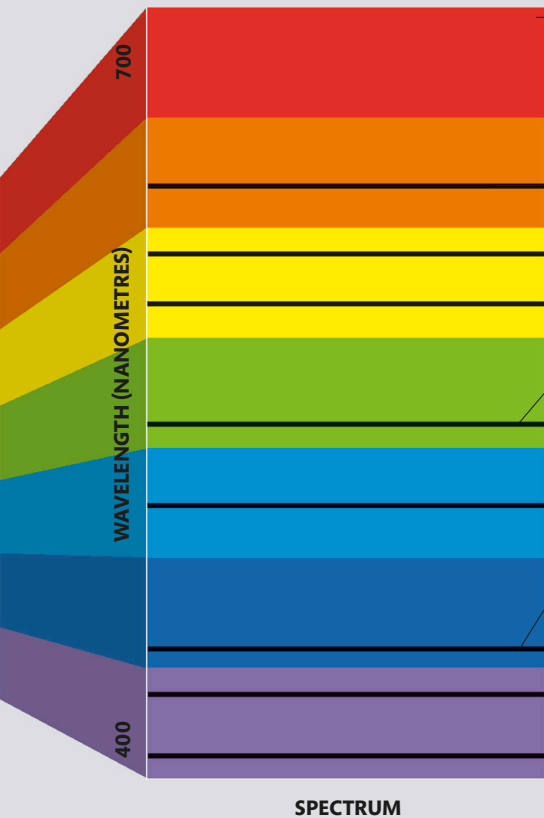


SPECTROGRAPHS CAN REVEAL HOW QUICKLY STARS MOVE



WHO FIRST ANALYSED STARLIGHT?

Physicist Joseph von Fraunhofer invented the spectroscope in 1814 and used it to study the Sun's spectra. The absorption lines he found are named in his honour.



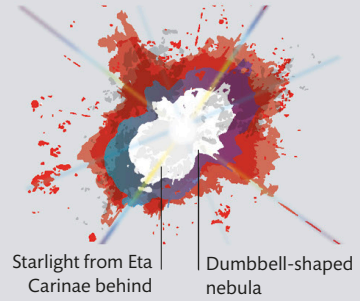
In electromagnetic spectrum, visible light ranges from red to violet; our eyes can detect wavelengths from around 400 to 700 nanometres

Each element produces its own unique pattern of black absorption lines, enabling astronomers to detect their presence in a star

Width of lines appearing on a spectrum varies depending on instrument used and temperature of material

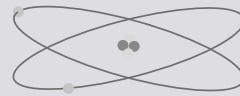
In this absorption spectrum (see below), black lines are dips where specific wavelengths of light are missing

Unique chemical fingerprint
Each star has its own spectrum, with each spectrum revealing exactly what materials are present in the star and its atmosphere. Spectra can help astronomers tell stars apart and reveal what stars have in common.



Stars with unusual spectra

Analysing the spectrum of the double supergiant Eta Carinae, hidden from direct view by a nebula formed from ejected stellar material 170 years ago, shows that the nebula is rich in nickel and iron.



HELIUM WAS ONLY DISCOVERED IN 1868 WHILE ASTRONOMERS WERE STUDYING THE SPECTRA OF THE SUN

Types of spectrum

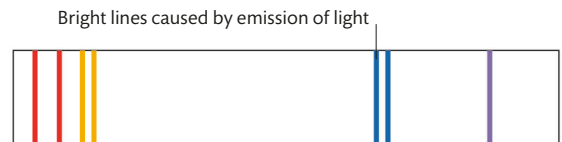
Depending on the object viewed, a spectroscope can produce three different types of spectrum. A continuous spectrum is created by a solid or a hot, dense gas, and it looks like a rainbow, with all the wavelengths of visible light represented. An absorption spectrum can be produced by a hot object like a star seen through a cooler gas. This type of spectrum is caused by atoms in a gas cloud absorbing the star's energy at specific wavelengths and then re-emitting them randomly. An emission spectrum is produced by a hot, low-density gas, which emits light at specific wavelengths only. It appears as a series of bright lines, each corresponding to a wavelength at which emission takes place.

Distinctive patterns

The three types of spectrum produce identifiable patterns. An absorption spectrum looks like a continuous spectrum minus the emission lines. Light from the Sun is very nearly a continuous spectrum but gases in its atmosphere absorb certain wavelengths of light, producing an absorption spectrum.



CONTINUOUS SPECTRUM



EMISSION SPECTRUM



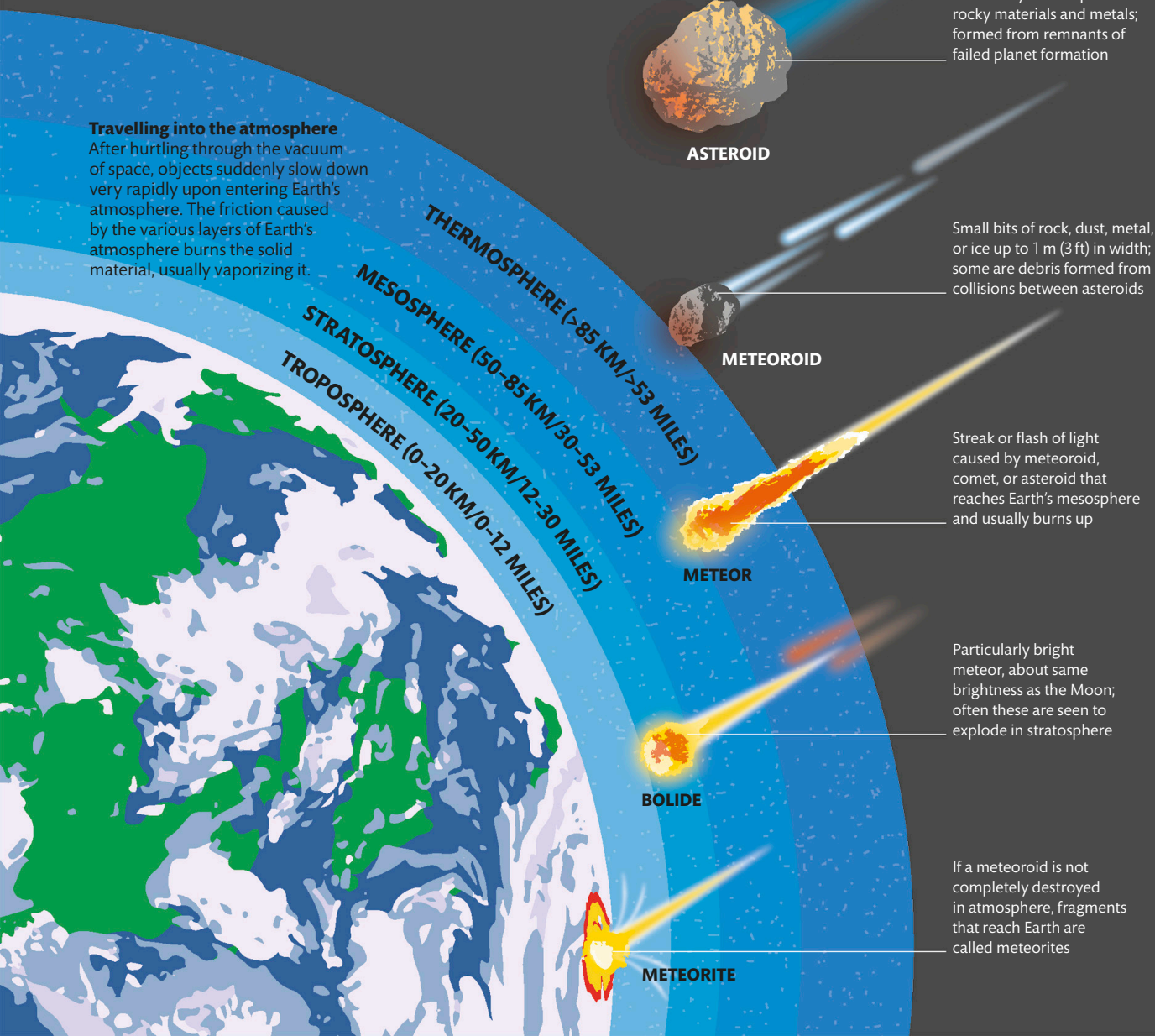
ABSORPTION SPECTRUM

Rocks from space

Many bodies of rock – as well as ice and metal – orbit the Sun. Some, such as comets and asteroids, are vast. Meteoroids are much smaller, and when they enter Earth's atmosphere, they are known as meteors, or shooting stars. The few meteors that are not completely vaporized and go on to strike Earth's surface are called meteorites.

Travelling into the atmosphere

After hurtling through the vacuum of space, objects suddenly slow down very rapidly upon entering Earth's atmosphere. The friction caused by the various layers of Earth's atmosphere burns the solid material, usually vaporizing it.



Small nucleus of ice and dust surrounded by bright cloud, or coma, of gas and dust

COMET

Solid body made up of rocky materials and metals; formed from remnants of failed planet formation

ASTEROID

Small bits of rock, dust, metal, or ice up to 1 m (3 ft) in width; some are debris formed from collisions between asteroids

METEOROID

Streak or flash of light caused by meteoroid, comet, or asteroid that reaches Earth's mesosphere and usually burns up

METEOR

Particularly bright meteor, about same brightness as the Moon; often these are seen to explode in stratosphere

BOLIDE

If a meteoroid is not completely destroyed in atmosphere, fragments that reach Earth are called meteorites

METEORITE



Types of rock

There are lots of fragments of rock moving around the Solar System, left over from when the planets and moons were forming. Objects made of rock, up to 1 m (3 ft) in size, are termed meteoroids. Rocky objects larger than this, but too small to be spherical like a planet, are generally asteroids or comets. Asteroids can be up to 1,000 km (600 miles) in size, while comets are smaller, up to around 40 km (25 miles). Most asteroids are in the Main Belt between Mars and Jupiter (see pp.60–61). Comets originate much further from Earth, which makes them cold enough to contain ice. When parts of these objects enter Earth's atmosphere and burn up, they create meteors.



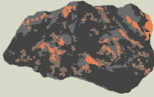
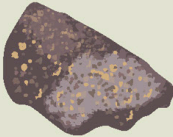

**EACH DAY, MILLIONS
OF METEOROIDS
BURN UP IN EARTH'S
ATMOSPHERE**

WHAT'S THE BIGGEST RECORDED METEORITE TO HIT EARTH?

The biggest intact meteorite is the Hoba meteorite, found in Namibia. It is thought to have fallen to Earth 80,000 years ago and weighs 60 tons (12,000 lbs).

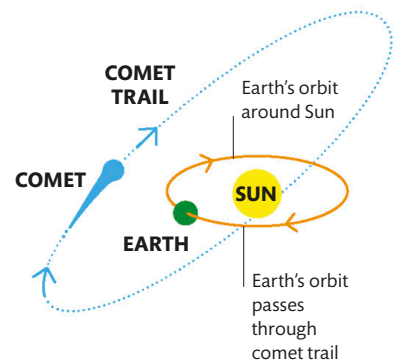
Meteorites

Meteorites are divided into three main types: iron, stony, and stony-iron. Meteorites often feature a burned, shiny exterior created as their outer surface melts when passing through the atmosphere. Some meteorites comprise material that originally formed the rocky planets, thus providing a glimpse into the conditions at the beginning of our Solar System.

TYPES OF METEORITE			
Meteorite type	Composition	Origin	Percentage of meteorites
IRON 	Composed mainly of iron-nickel alloy and small amounts of other minerals.	Thought to be the cores of asteroids that melted early in their history.	5.4 per cent
STONY 	Silicate minerals; they are divided into two groups: achondrites and chondrites. Chondrites contain once-molten grains called chondrules.	Achondrites formed by melting of parent asteroids; chondrites formed in the primitive Solar System from dust, ice, and grit.	93.3 per cent
STONY-IRON 	Roughly equal amounts of metal and silicate crystals; they are divided into two groups: pallasites and mesosiderites.	Pallasites formed between a metal core and an outer silicate mantle; mesosiderites form through a collision between asteroids.	1.3 per cent

METEOR SHOWERS

Comets are always losing bits of themselves, leaving behind a trail in their wake. When Earth's orbit of the Sun brings us through that trail, we experience a meteor shower. During these periods, it can be possible to witness tens to hundreds of meteors radiating from a common point in the night sky in just an hour. Meteor showers are usually named after a star or constellation near where the meteors originate from in the sky.

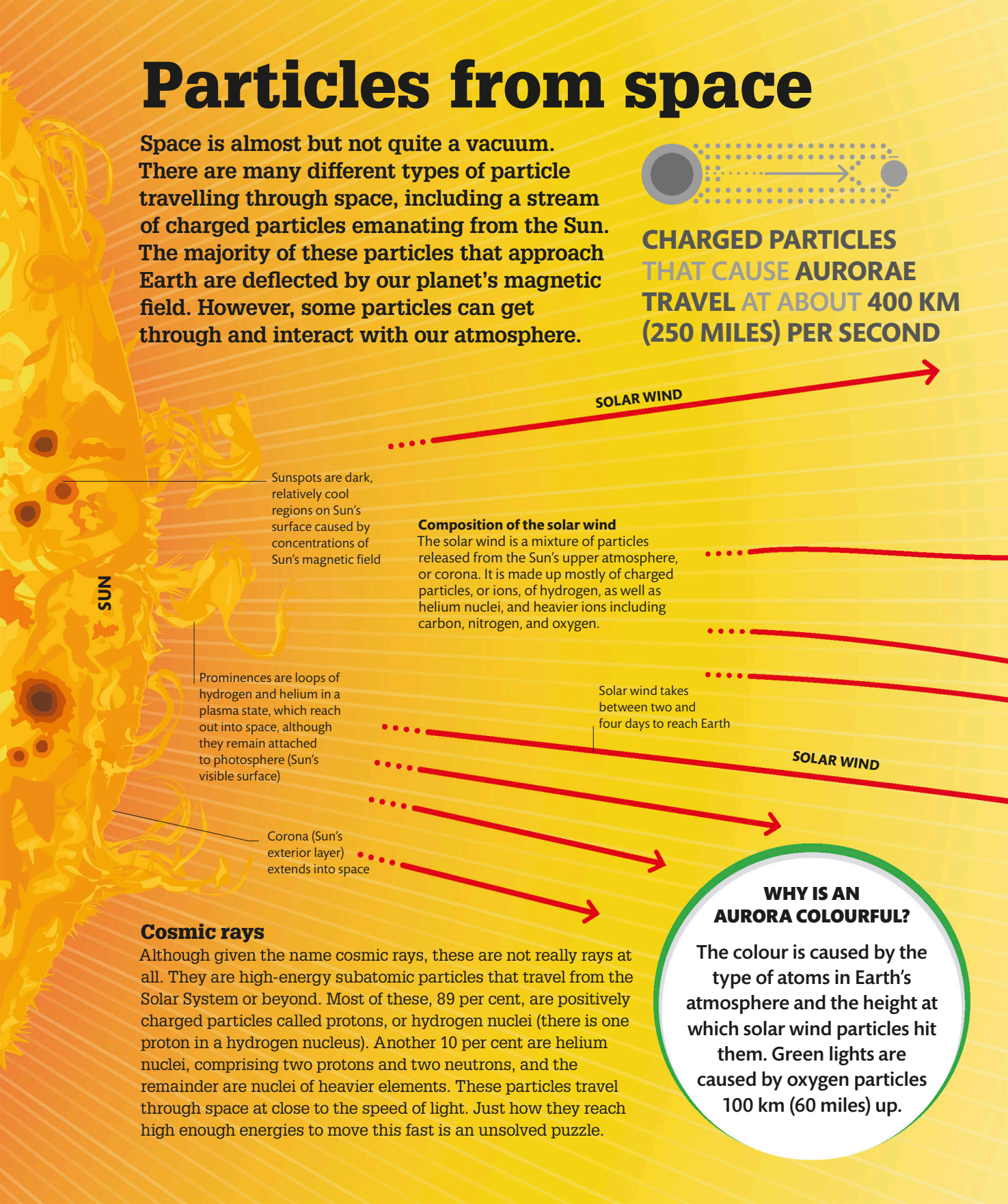


Particles from space

Space is almost but not quite a vacuum. There are many different types of particle travelling through space, including a stream of charged particles emanating from the Sun. The majority of these particles that approach Earth are deflected by our planet's magnetic field. However, some particles can get through and interact with our atmosphere.



**CHARGED PARTICLES
THAT CAUSE AURORAE
TRAVEL AT ABOUT 400 KM
(250 MILES) PER SECOND**



Sunspots are dark, relatively cool regions on Sun's surface caused by concentrations of Sun's magnetic field

Composition of the solar wind

The solar wind is a mixture of particles released from the Sun's upper atmosphere, or corona. It is made up mostly of charged particles, or ions, of hydrogen, as well as helium nuclei, and heavier ions including carbon, nitrogen, and oxygen.

Prominences are loops of hydrogen and helium in a plasma state, which reach out into space, although they remain attached to photosphere (Sun's visible surface)

Solar wind takes between two and four days to reach Earth

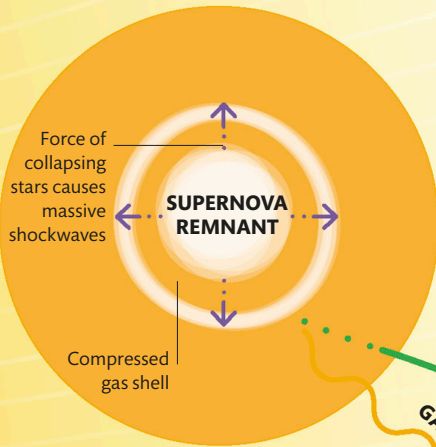
Corona (Sun's exterior layer) extends into space

Cosmic rays

Although given the name cosmic rays, these are not really rays at all. They are high-energy subatomic particles that travel from the Solar System or beyond. Most of these, 89 per cent, are positively charged particles called protons, or hydrogen nuclei (there is one proton in a hydrogen nucleus). Another 10 per cent are helium nuclei, comprising two protons and two neutrons, and the remainder are nuclei of heavier elements. These particles travel through space at close to the speed of light. Just how they reach high enough energies to move this fast is an unsolved puzzle.

WHY IS AN AURORA COLOURFUL?

The colour is caused by the type of atoms in Earth's atmosphere and the height at which solar wind particles hit them. Green lights are caused by oxygen particles 100 km (60 miles) up.



The solar wind

Charged particles from the Sun, known as the solar wind, make up the lowest-energy cosmic rays that reach Earth. Aurorae are caused by these particles entering Earth's atmosphere and colliding with gas particles in the air. This provides the gas particles with extra energy and excites electrons within them to a higher-energy state. This state is unstable, so the electrons will return to their previous state, releasing the energy as a photon, or a particle of light.

Supernova sources

When huge stars explode, they create shock waves, which are thought to accelerate charged particles and gamma rays (see pp.152-53) to very high energies. While charged particles are deflected by Earth's magnetic field away from Earth, electrically neutral gamma rays are not.

Defending Earth

Electricity in Earth's molten iron core generates a magnetic field, which forms a protective bubble around the planet. This helps protect us from charged particles, many of which are deflected around Earth.

Spherical outer radiation belt traps incoming solar wind particles

Aurorae around south pole are known as aurora australis, or southern lights

Magnetopause, the edge of Earth's magnetic field

Deflected charged particles pass through magnetosphere at areas of weaker field strength called cusps; from there they travel to Earth's magnetically charged poles

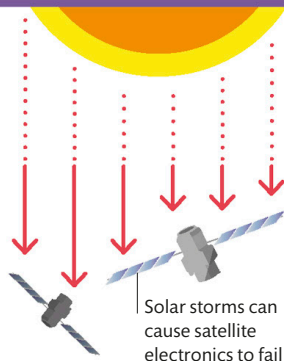
Aurorae manifest in huge rings, called auroral ovals, above Earth's magnetic poles

Inner radiation belt, consisting mainly of highly energetic protons

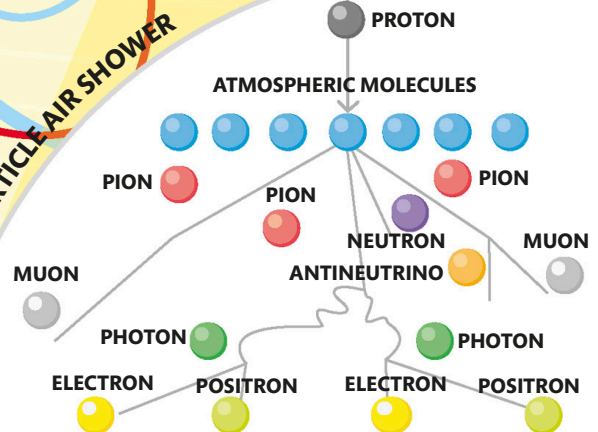
Most particles are deflected away from Earth by magnetic field

SPACE WEATHER

The magnetic activity on the surface of the Sun creates a type of weather called space weather. Mass ejections from the Sun's corona, for example, can create geomagnetic storms. In the most extreme cases, these can impact orbiting satellites and even power grids on Earth's surface.



PARTICLE AIR SHOWER



Descent through Earth's atmosphere

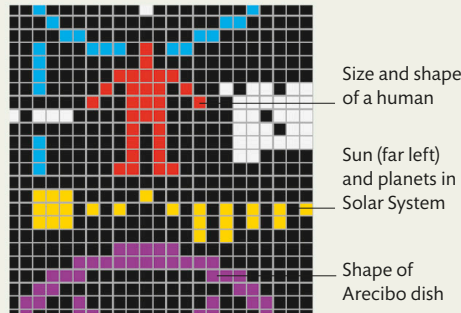
Cosmic rays interact with molecules in Earth's atmosphere, producing subatomic particles called pions. In turn, these may decay or collide with other particles in the air and create a cascade of further particles.

Looking for aliens

The question of whether life exists beyond Earth has captured the imaginations of humans for centuries. Attempts to identify extraterrestrial life principally involve launching probes into space and scanning for radio signals that may have been sent by aliens.

Trying to make contact

In 1974, radio signals were transmitted for the first time to try to make contact with extraterrestrial life. The Search for Extraterrestrial Intelligence (SETI) Institute, launched in 1985, built on these efforts. Later developments include the completion of the Five-hundred-metre Spherical Aperture Telescope (FAST) in 2019. One of its functions is to listen for alien radio signals.

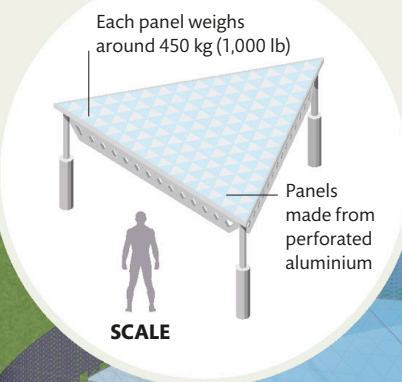


Arecibo message

In 1974, a radio message was sent from the Arecibo Observatory to star cluster M13. It included data about humanity and Earth.

Adjustable panels

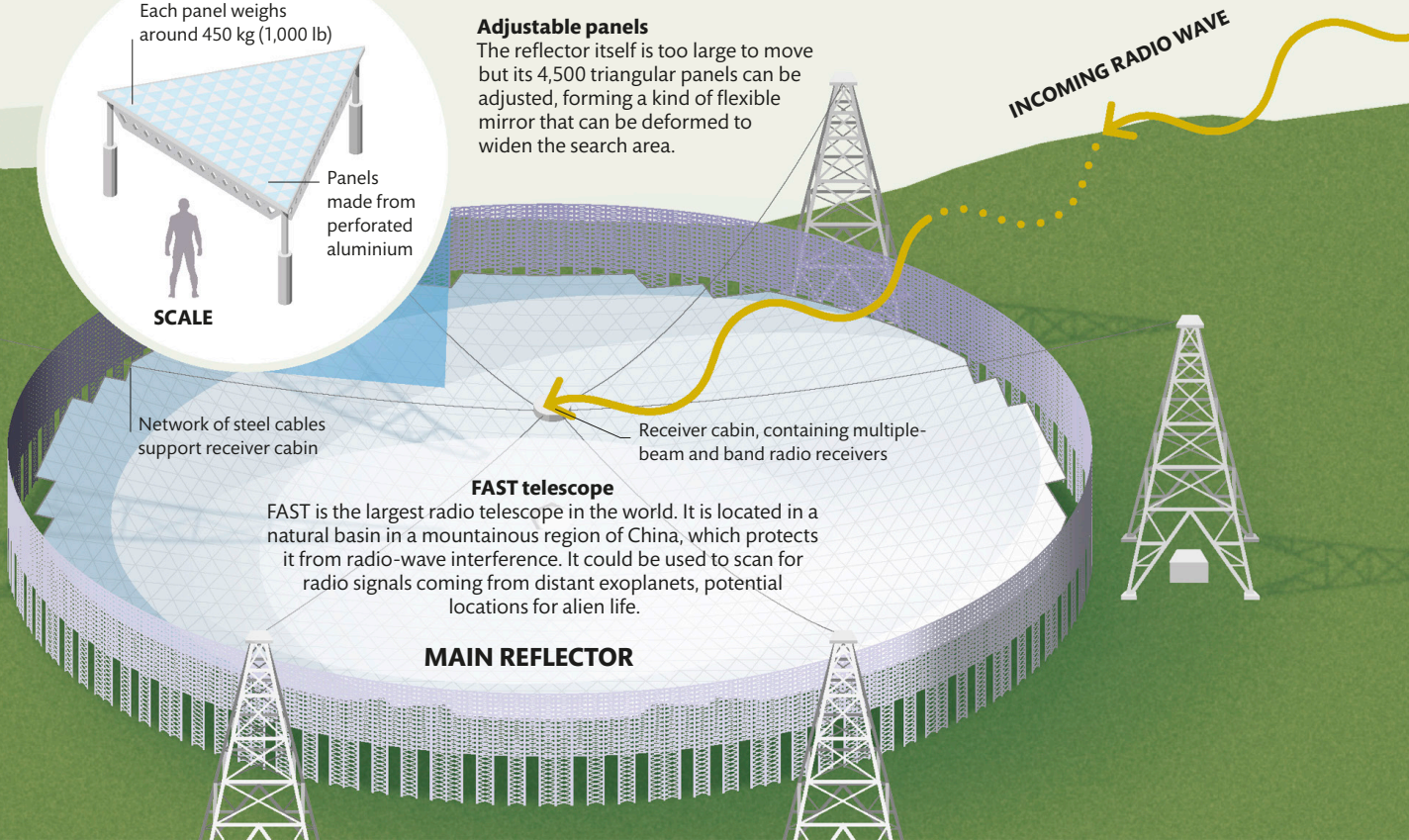
The reflector itself is too large to move but its 4,500 triangular panels can be adjusted, forming a kind of flexible mirror that can be deformed to widen the search area.



WHAT IS A FAST RADIO BURST?

Fast radio bursts are mysterious pulses of powerful radio waves that last for only a few milliseconds, and usually come from distant galaxies. Their origin is unknown.

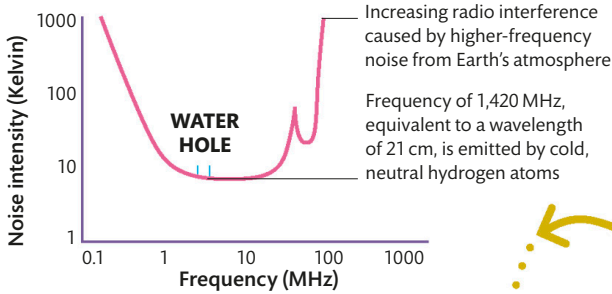
THE FAST TELESCOPE
HAS A COLLECTING AREA EQUIVALENT TO 750 TENNIS COURTS





Cosmic quiet zone

The "water hole" is a band of the electromagnetic spectrum between 1,420 and 1,640 MHz in which interference is minimal. The frequency range is associated with emissions from hydrogen atoms and hydroxyl particles, which together constitute water. It is a popular listening frequency for radio telescopes.



Aurora could emit radio waves powerful enough to be detected by radio telescopes on Earth

AURORA

Strong magnetic field emanates from red dwarf star

RED DWARF

An aurora forms, produced by interaction between a nearby rocky exoplanet and red dwarf

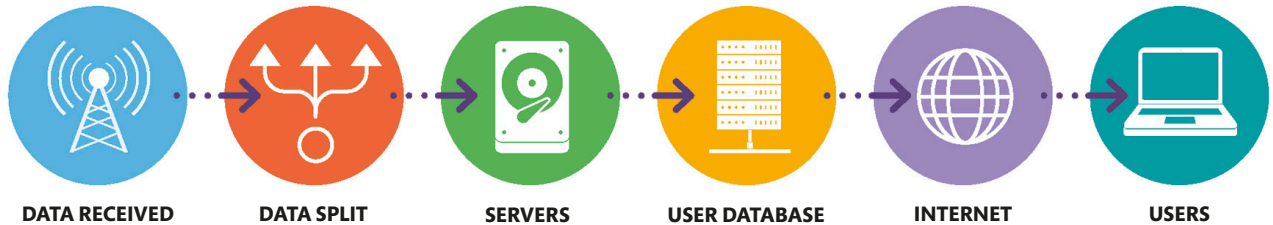
EXOPLANET

How SETI@Home worked

This citizen science experiment, which ran from 1999 to 2020, allowed anyone with a computer and an internet connection to help in the search for extraterrestrial life. Users installed a free program, which then downloaded and analysed 107-second units of data collected from radio telescopes.

Listening for aliens

One way of trying to find aliens is by listening for signals from intelligent life, sent out on purpose to make contact with other intelligent life forms. This is done by searching for electromagnetic radiation in the radio frequency and ruling out any other possible sources for that radiation. SETI@Home was a unique program that has been at the forefront of this endeavour. The collected data is still being analysed.



THE DRAKE EQUATION

This is an equation used to estimate not only how likely it is that life exists outside our planet, but also the odds of humans being able to find intelligent life in the Universe. First proposed by radio astronomer Frank Drake in 1961, the equation calculates the number of civilizations potentially capable of communication by multiplying several variables.

Number of advanced civilizations in Milky Way	Fraction of stars with planetary systems	Fraction of those worlds that give rise to life	Fraction of civilizations with communications technology											
N	$=$	R_*	\times	f_p	\times	n_e	\times	f_e	\times	f_i	\times	f_c	\times	L
Rate of formation of stars in galaxy		Number of life-supporting worlds per planetary system		Fraction of those worlds with intelligent life		Average lifetime of communicating civilization								



THE SOLAR SYSTEM

30 TRILLION KM (18 TRILLION MILES) – THE DIAMETER OF THE SOLAR SYSTEM



Main Belt is formed
of millions of rocky
asteroids

Sun is source of most
light, heat, and radiation
in Solar System

Earth is perfectly positioned
to access solar energy
without being too hot

Mercury is
smallest planet
in Solar System

Venus is hottest planet
and only slightly
smaller than Earth

Mars is cold and dusty
and has seen extensive
volcanic activity

SUN

MERCURY

VENUS

EARTH

MARS



The planets

The eight planets of the Solar System all travel anticlockwise around the Sun in elliptical orbits, in almost the same plane. Close to the Sun are four rocky planets, including Earth, and further away are four giant planets.

Structure of the Solar System

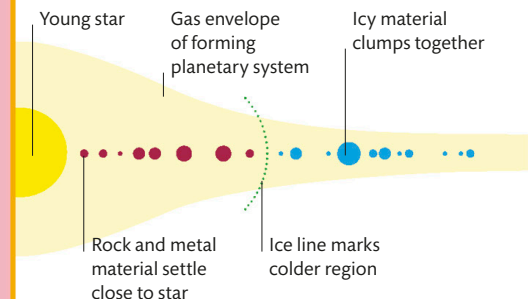
The Solar System is structured around the Sun, with a clear distinction between small, rocky bodies close to the Sun and giant gas and ice planets much further away.

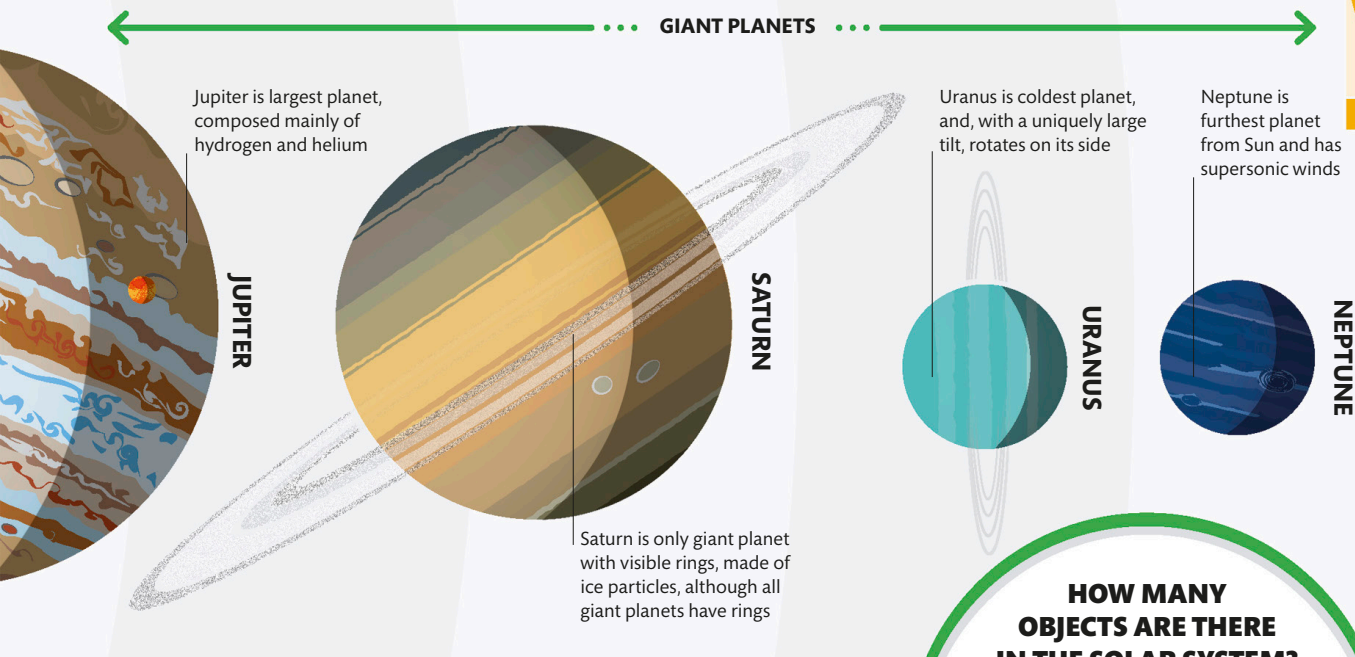
Objects in the Solar System

The Solar System comprises all of the objects held by the Sun's powerful gravitational pull. The largest such objects are the eight known planets, which have over 200 moons between them. Rocky asteroids and icy comets race through the spaces between the planets and the five confirmed dwarf planets. The Solar System extends to the edge of the Oort Cloud (see pp.84–85) – around 100,000 times the distance between Earth and the Sun. It is just one of hundreds of billions of similar structures embedded in the vast stellar metropolis known as the Milky Way galaxy.

THE ICE LINE

The ice line marks the point in a forming planetary system where temperatures drop below the freezing point of water, ammonia, and methane. Beyond this line, icy material gathers to form giant planets. Closer to the star, only rock and metal can withstand the heat.



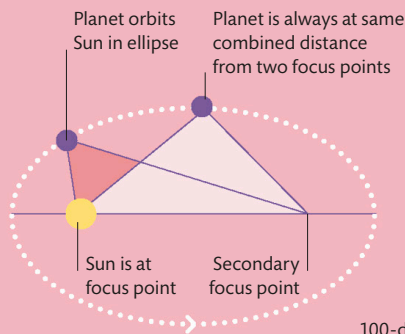


HOW MANY OBJECTS ARE THERE IN THE SOLAR SYSTEM?

The exact number is unknown, but more than half a million Solar System bodies have official names and there are at least another 300,000 yet to be named.

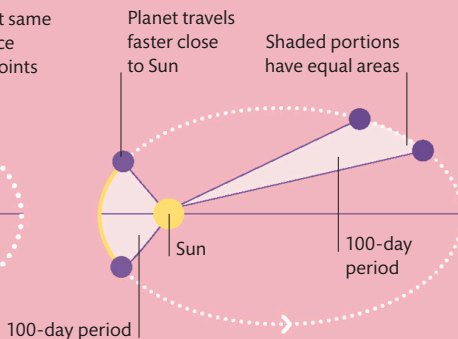
Kepler's laws of planetary motion

German astronomer Johannes Kepler used detailed observations of the movements of the planets to formulate three mathematical laws. Later, Isaac Newton showed how Kepler's laws followed naturally from his law of universal gravitation. The three laws describe the shapes of orbits and how the speed of motion is affected by distance from the Sun.



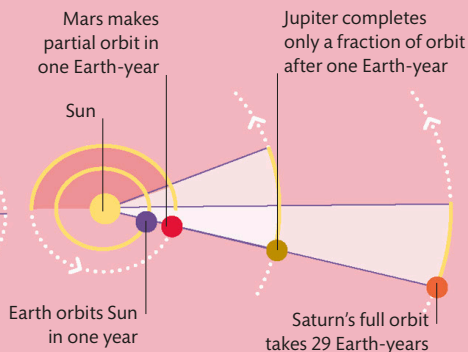
Law 1

Kepler's first law states that the orbit of a planet is an ellipse, with two focus points and the Sun at one of these focus points. The more elliptical an orbit is, the more orbital eccentricity it is said to have.



Law 2

Kepler noticed that a planet speeds up when it is close to the Sun and slows down when it is further away. He found that the line from the Sun to the planet sweeps out equal areas in equal periods of time.



Law 3

Planets take longer to orbit the further away they are from the Sun. Kepler found a simple formula that links the orbital periods of the planets with the size of their orbits.

Birth of the Solar System

The Solar System formed about 4.5 billion years ago. By studying young star systems in the Milky Way, and running computer simulations, astronomers have begun to understand how the Solar System probably came into being.

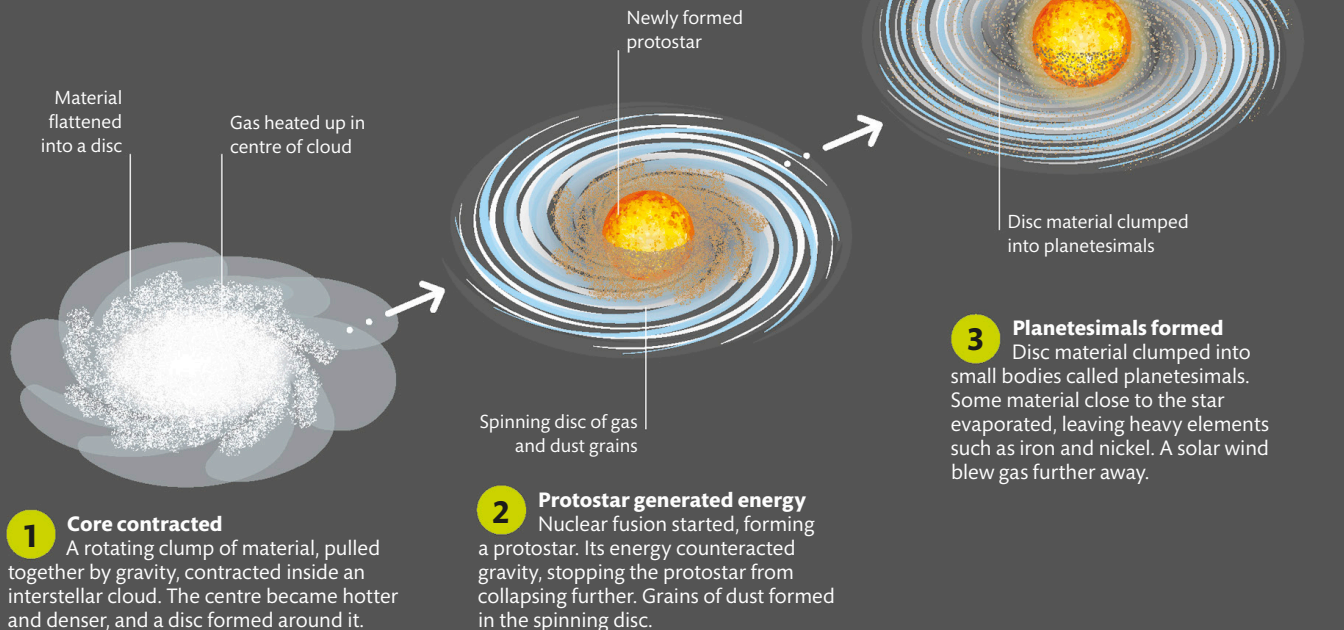
The solar nebula

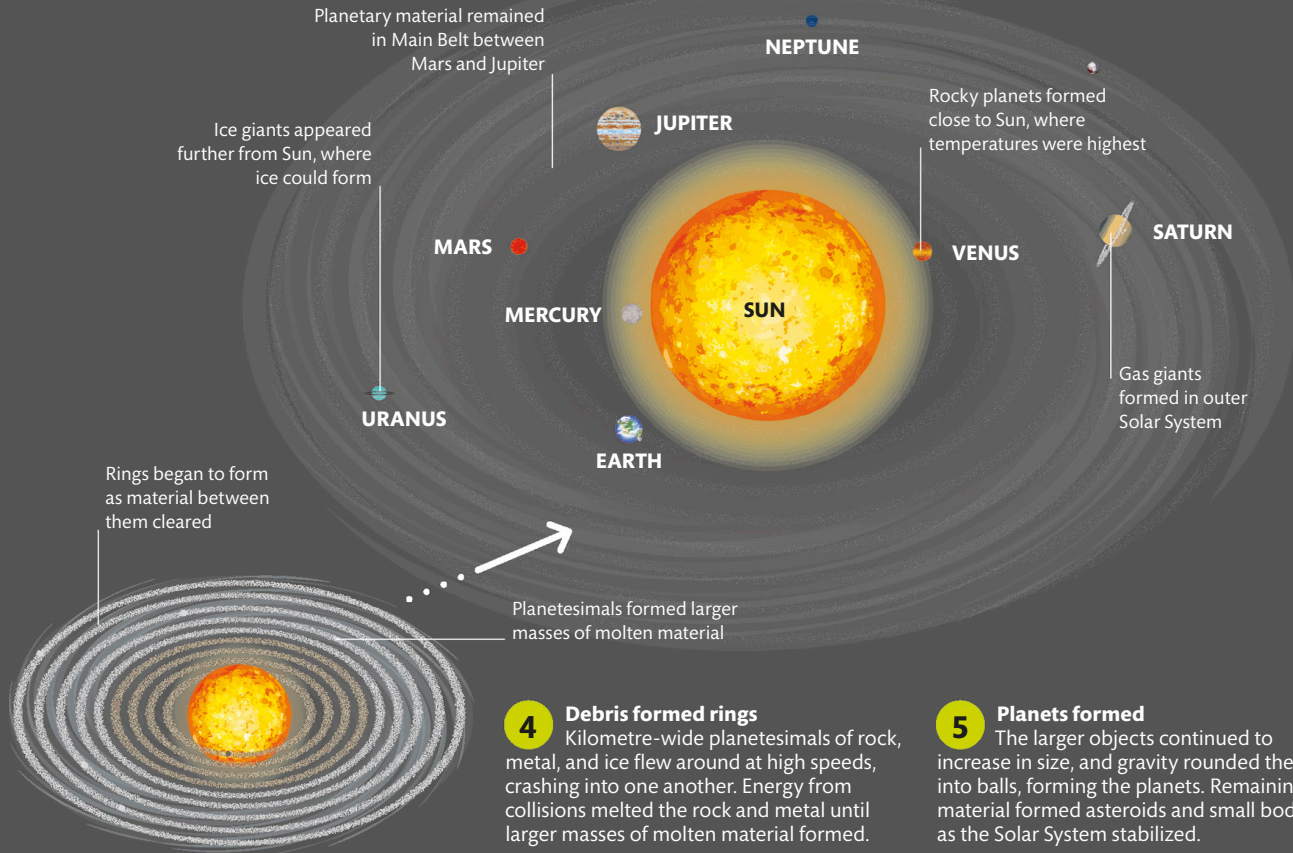
The most widely accepted idea of how the Solar System formed starts with the birth of the Sun, when a ball of gas and dust, called a core, was pulled together by gravity inside a giant molecular cloud, possibly triggered by a nearby exploding star (see pp.92–93). As the core collapsed, more material was drawn in, adding to its central density and causing it to spin increasingly fast. A flat protoplanetary disc of gas and dust, called a solar nebula, grew around the newly formed Sun at the centre. Over millions of years, gravity continued to draw the disc material together, creating the system of asteroids, moons, and planets that now orbit the Sun.

WHICH PLANET FORMED FIRST?

Astronomers believe that the gas giant Jupiter was the first planet to form and that it then influenced the way other planets formed. The rocky planets may have formed last.

0.01 PER CENT
OF THE NEBULA
MATERIAL ENDED
UP IN THE PLANETS



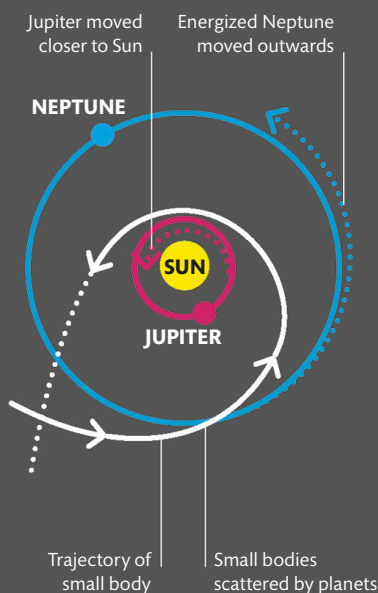


Planetary migration

It took millions of years for the Solar System to settle into its present configuration. The newly formed planets migrated as they interacted with each other and debris remaining from their formation. This process also depleted the Main Belt and the Kuiper Belt beyond Neptune (see pp.82–83), by spreading debris far and wide.

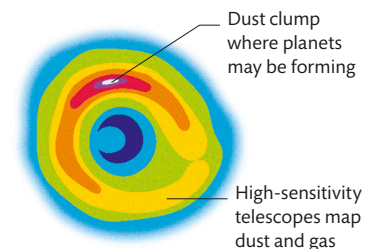
Altered orbits

Models of planetary migration suggest that Jupiter moved inwards, while Saturn, Uranus, and Neptune – energized by the scattering of smaller bodies – edged further out. Neptune and Uranus even swapped position.



PROTOPLANETARY DISCS

New solar systems form in flat, dusty discs, called protoplanetary discs, that swirl around newly formed stars. Clumps of dust appear where planets are forming.



PROTOPLANETARY DISC

The Sun

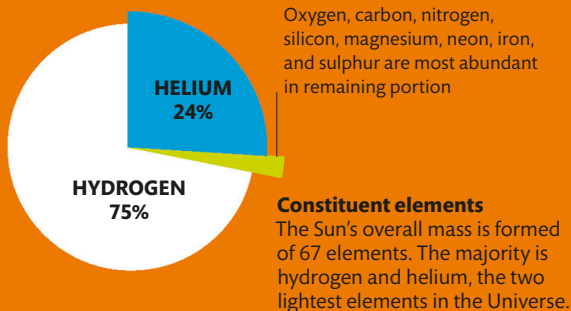
The Sun is an enormous nuclear powerhouse at the heart of our Solar System. It provides the gravitational force that binds the Solar System together, and its energy floods the planets with heat and light.

Inside the Sun

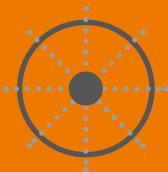
Solar energy begins its odyssey deep in the core of the Sun. The crush of gravity sends temperatures soaring to nearly 16 million°C (29 million°F) and the pressure is 100 billion times the atmospheric pressure on Earth. These extreme conditions allow nuclear fusion to take place, converting 620 million tonnes (680 million tons) of hydrogen per second into helium and energy (see p.90). This energy journeys through the radiative and convective zones to reach the visible surface.

The Sun's elements

Astronomers use spectroscopy – the close study of a spectrum – to identify chemical elements in the Sun (see pp.26–27). Atoms of these elements can be identified because they absorb or emit light of very specific colours. The Sun is so hot that some of these atoms become electrically charged plasma, causing the Sun's plasma state.



RADIATION TAKES UP TO 1 MILLION YEARS TO TRAVEL FROM THE CORE TO THE SOLAR SURFACE



Radiation slowly diffuses outwards through radiative zone

Radiative zone is so dense that radiation only travels 1 mm (0.04 in) before encountering an obstacle

Internal structure

It takes up to 1 million years for energy from the hot, dense core to travel through the radiative and convective zones, and reach the surface. The photosphere is visible from Earth, but it is covered by two layers of atmosphere, the corona and chromosphere.

CORE

Core takes up roughly inner quarter of Sun and is eight times denser than gold



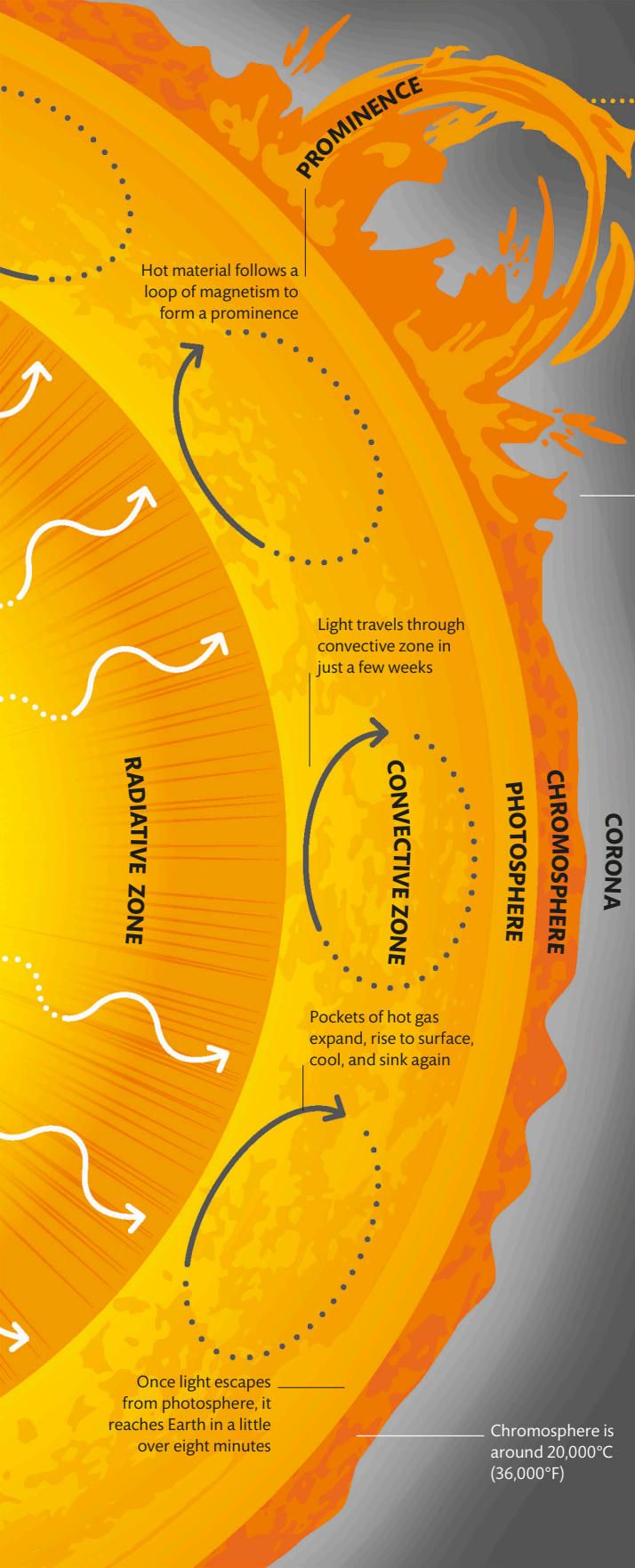
HOW BIG IS THE SUN?

The Sun is 1.4 million km (870,000 miles) wide, and over a million Earths could fit inside it. Most stars are smaller than the Sun.

Corona, Sun's outer atmosphere, is visible during solar eclipses

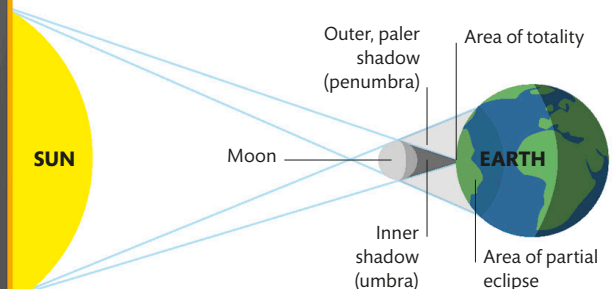
Exterior layers

The Sun's visible surface, the photosphere, is also the first layer of its atmosphere. Flamelike eruptions called prominences, and rapid energy releases known as flares, shoot up from here into the chromosphere and corona above. The corona is over 1 million°C (1.8 million°F), far hotter than the layers of atmosphere below it. This disparity in temperatures is one of the most confounding solar mysteries. Astronomers are still searching for the mechanism that injects energy into the corona, as flares alone are not sufficient.



SOLAR ECLIPSES

The Sun's faint corona is best seen during a total solar eclipse. During these spectacular events – which occur approximately every 18 months – the Moon blocks out the main glare of the Sun. Totality occurs when the Moon completely covers the main disc of the Sun. At that point, the Moon's shadow (or umbra) engulfs a portion of Earth.



Chromosphere is around 20,000°C (36,000°F)

The solar cycle

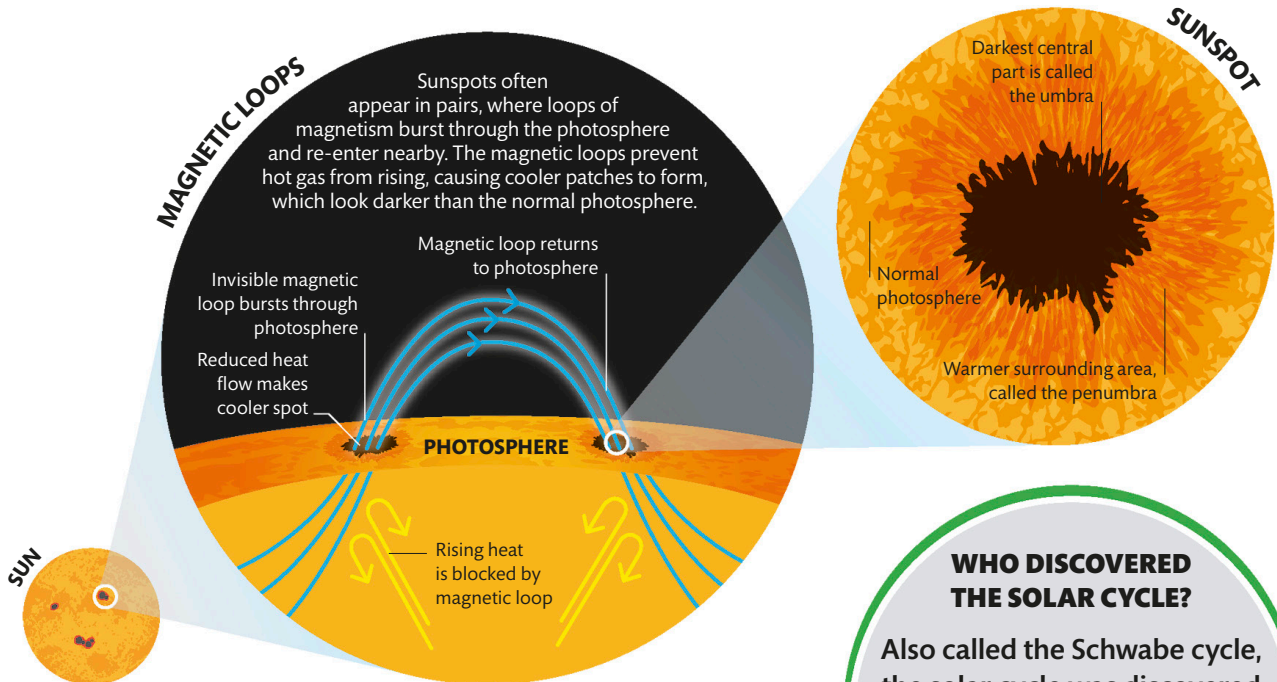
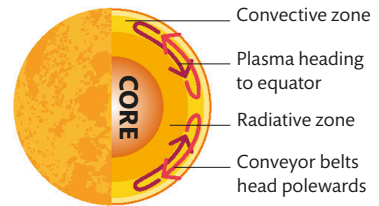
Generations of astronomers have watched solar activity rise and fall in a repeating pattern called the solar cycle. Solar activity has been scrutinized in unprecedented detail since solar telescopes were first launched into space in the 1990s.

Sunspots

The most conspicuous feature of the solar cycle is sunspots. They look like deep bruises on the Sun's surface, but are in fact cooler regions of the photosphere at about 3,500°C (6,300°F). Magnetic fields stretch deep inside the Sun as it rotates, causing tubes of magnetism to break through the photosphere and make cup-shaped dips. Sunspots last for only a few weeks, appearing in different zones throughout the cycle.

SOLAR CONVEYOR BELTS

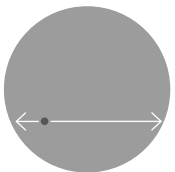
Giant conveyor belts of plasma churn inside the Sun's convective zone. They drag magnetic fields towards the surface, and transfer material from the equator towards the poles at speeds of about 50 kph (30 mph). This causes sunspots to appear closer to the equator during the solar cycle.



WHO DISCOVERED THE SOLAR CYCLE?

Also called the Schwabe cycle, the solar cycle was discovered in 1843 by Samuel Heinrich Schwabe, a German amateur astronomer, who made daily observations over 17 years.

THE LARGEST SUNSPOT
EVER RECORDED WAS
30 TIMES WIDER
THAN EARTH



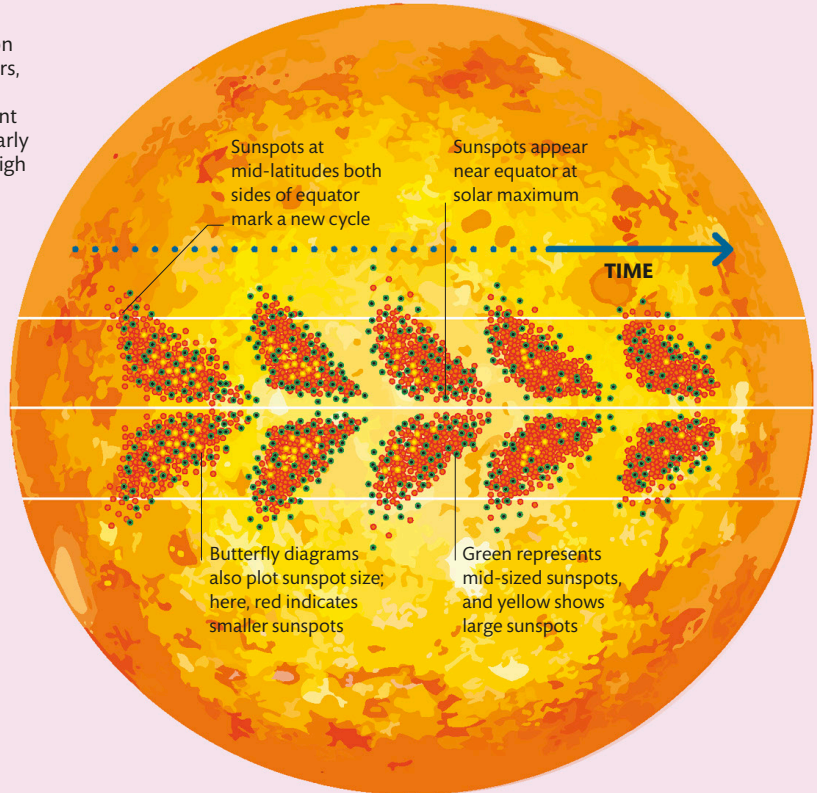
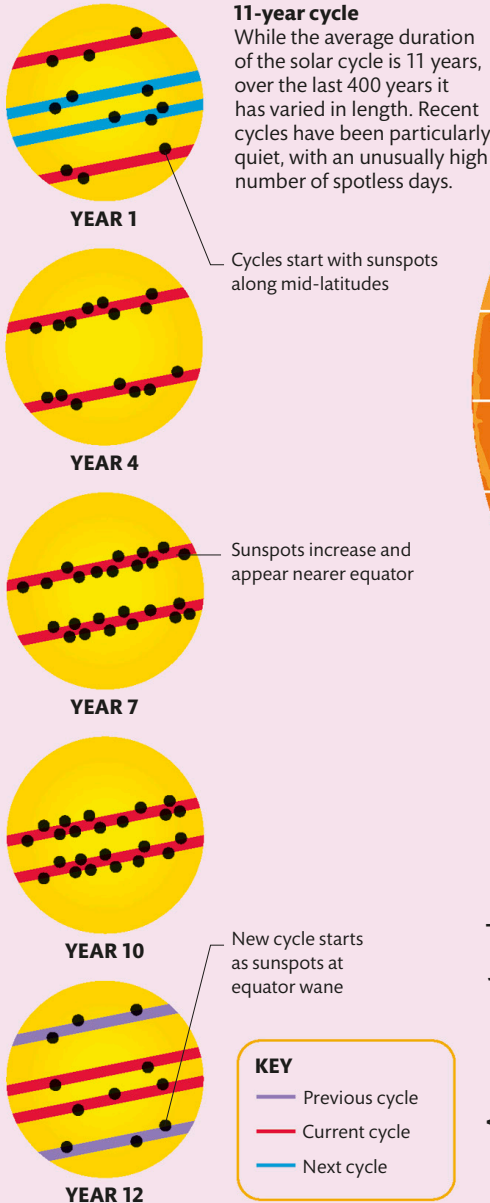


Solar maximum and minimum

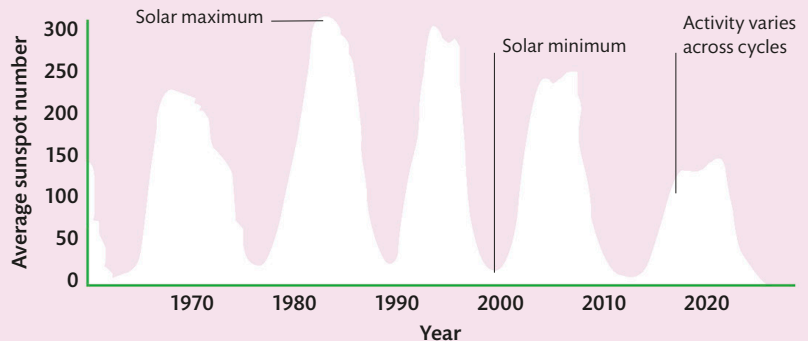
Sunspots are not the only kind of solar activity. Gigantic eruptions called coronal mass ejections burst from the corona, and rapid releases of stored magnetic energy cause solar flares. This activity is more frequent at solar maximum and declines at solar minimum, with important consequences on Earth. Increased solar activity generates spectacular aurorae near Earth's poles (see p.31), but it can also lead to power cuts, satellite failures, and radio blackouts.

Butterfly patterns

A famous diagram called the Butterfly Diagram – because of its resemblance to the flying insect – charts the movement of the sunspot zone over the course of a solar cycle. Sunspots gradually appear closer to the equator as solar maximum nears. Comparing multiple cycles in a graph shows the variations in activity across cycles.



BUTTERFLY DIAGRAM



Earth

Called the Blue Planet, because of the expansive ocean covering 71 per cent of its surface, Earth is a haven of life in space. It is the only place in the Universe unequivocally known to host living things.

Suitable for life

For life to endure on Earth, it needs to be protected from the ravages of space. Chief among these dangers is radiation from the Sun, which can damage living cells. However, Earth is enveloped in a magnetic field, arising from Earth's rotating iron core, that provides a protective shield. It helps to deflect high-energy particles from the Sun and exploding stars in the wider galaxy.

Internal layers

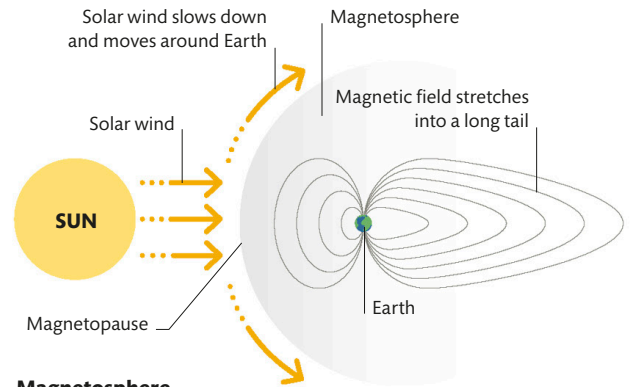
Earth's core has remained hot since the planet first formed and continues to be heated by the decay of radioactive elements such as uranium. The temperature at the centre of Earth is about 6,000°C (11,000°F), as hot as the Sun's surface. Molten material in the outer core moves and drives the magnetic field. Activity seen on the surface, such as volcanoes and earthquakes, is governed by heated material in the mantle rising through the mostly solid upper mantle and bursting through the crust.

EARTH'S CRUST HAS THE SAME RELATIVE THICKNESS AS THE SKIN ON AN APPLE



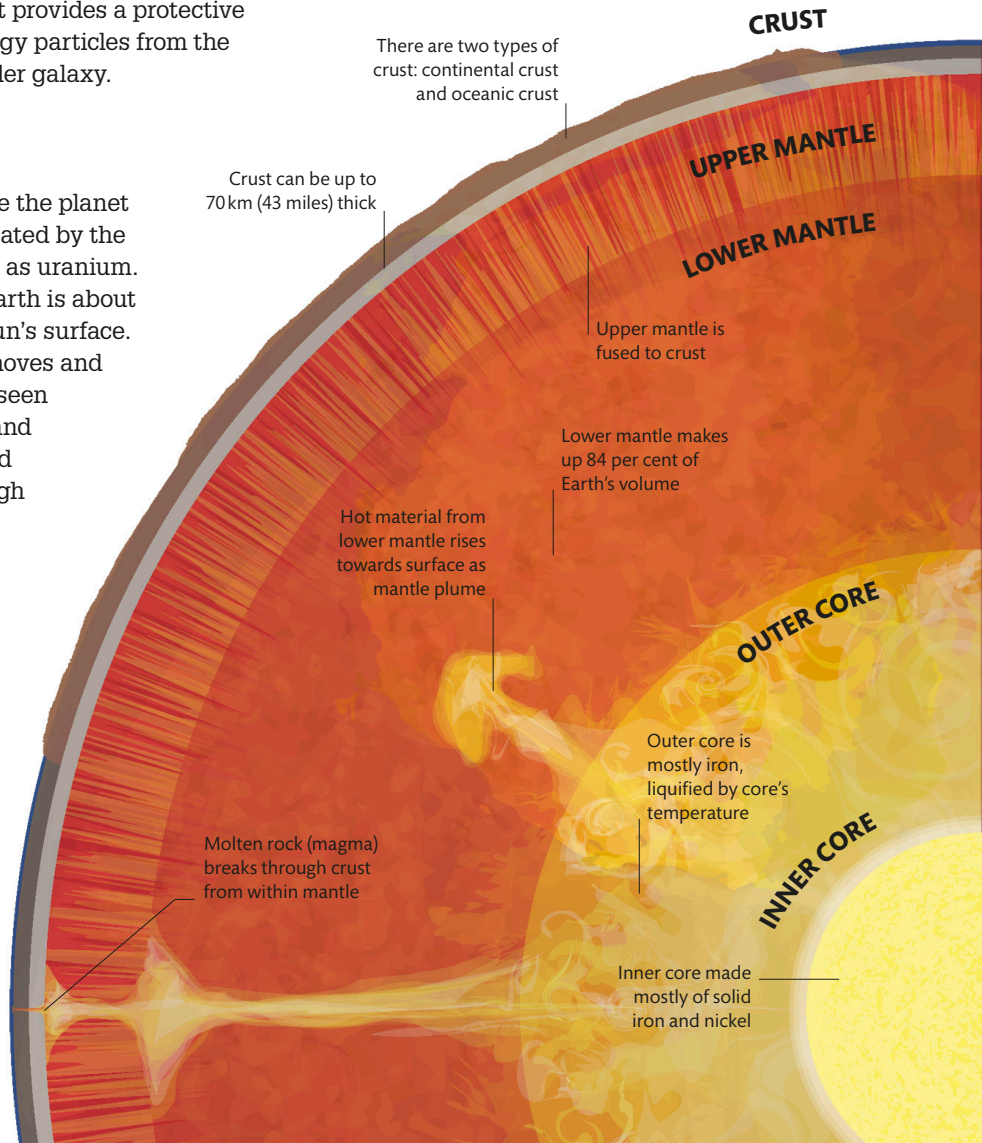
Heating the planet

The majority of the heat rising to Earth's surface is transported by convection – the same process as in the convective zone of the Sun (see pp.40–41).



Magnetosphere

The magnetosphere is a region where a magnetic field surrounds Earth. Charged particles in the solar wind slow at the surface of the magnetosphere, called the magnetopause. The field is deflected and blown into a long tail some 500 Earths wide.

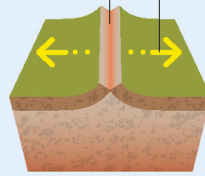




Surface and atmosphere

Earth's crust is incredibly thin and constantly changing. It is fused to the upper mantle and broken into pieces called tectonic plates that move around on deeper parts of the mantle below. Mountains and cracks form as the plates converge or diverge. Above all this, a protective atmosphere, composed mostly of nitrogen (78 per cent) and oxygen (21 per cent), extends for more than 600 km (370 miles).

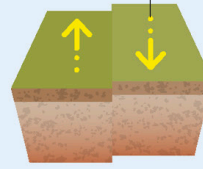
Tectonic plates pull away
Molten rock rises



Divergent boundary

Two tectonic plates move apart, and molten rock emerges from the mantle to fill the gap. The cooling rock forms a new piece of crust.

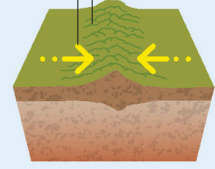
Plates neither collide
nor pull apart



Transform boundary

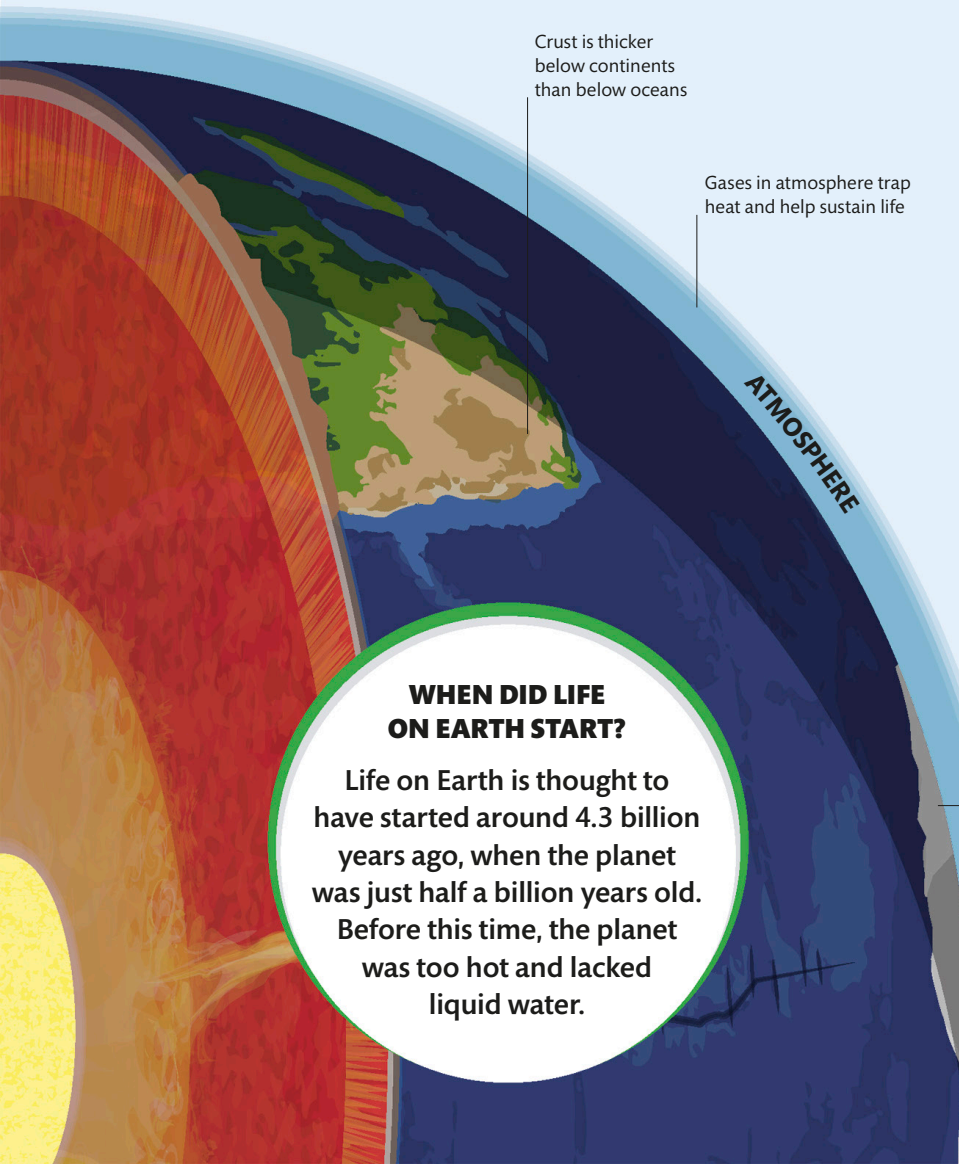
Tectonic plates slide past one another, creating cracks known as faults. Most faults are found at the bottom of the ocean.

Plates slowly collide
Earth's surface changes shape



Convergent boundary

Plates collide into one another, leading to earthquakes, volcanic activity, and a deformed crust. The Himalayas formed this way.



Crust is thicker
below continents
than below oceans

Gases in atmosphere trap
heat and help sustain life

ATMOSPHERE

WHEN DID LIFE ON EARTH START?

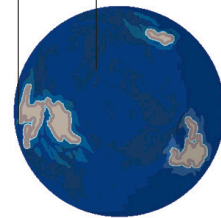
Life on Earth is thought to have started around 4.3 billion years ago, when the planet was just half a billion years old. Before this time, the planet was too hot and lacked liquid water.

WHERE DID EARTH'S WATER COME FROM?

Astronomers think water arrived on comets and asteroids, which bombarded the early Earth. These collisions left material containing water molecules deep inside Earth, from which water rose up and covered the surface.

Light rock material rose
to form continents

Liquid water covered
cooling Earth



FORMING OCEAN

Continents and oceans
are still changing shape
as tectonic plates move

Protective atmosphere

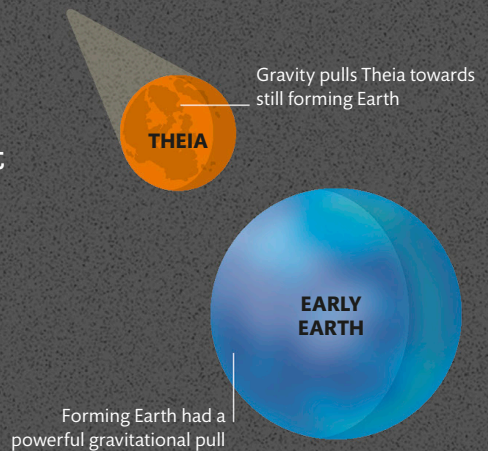
Ozone, a form of oxygen in the atmosphere, protects life on Earth from ultraviolet radiation. The atmosphere also breaks up smaller asteroids and comets before they can strike the surface (see pp.28–29).

The Moon

Earth's natural satellite, the Moon, is the nearest celestial body to Earth and the most familiar object in the night sky. It is a spectacular sight when viewed through binoculars or a telescope.

How did the Moon form?

The leading idea explaining the formation of the Moon is called the giant impact hypothesis. The hypothesis suggests that within Earth's first 100 million years it was hit by another planet, of a similar size to Mars, called Theia. After impact, most of the heavy elements from both planets, such as iron and nickel, stayed on Earth to form its heavy core. At the same time, lighter, rocky material was sprayed into orbit. Gradually, gravity brought some of this debris together to form the Moon.



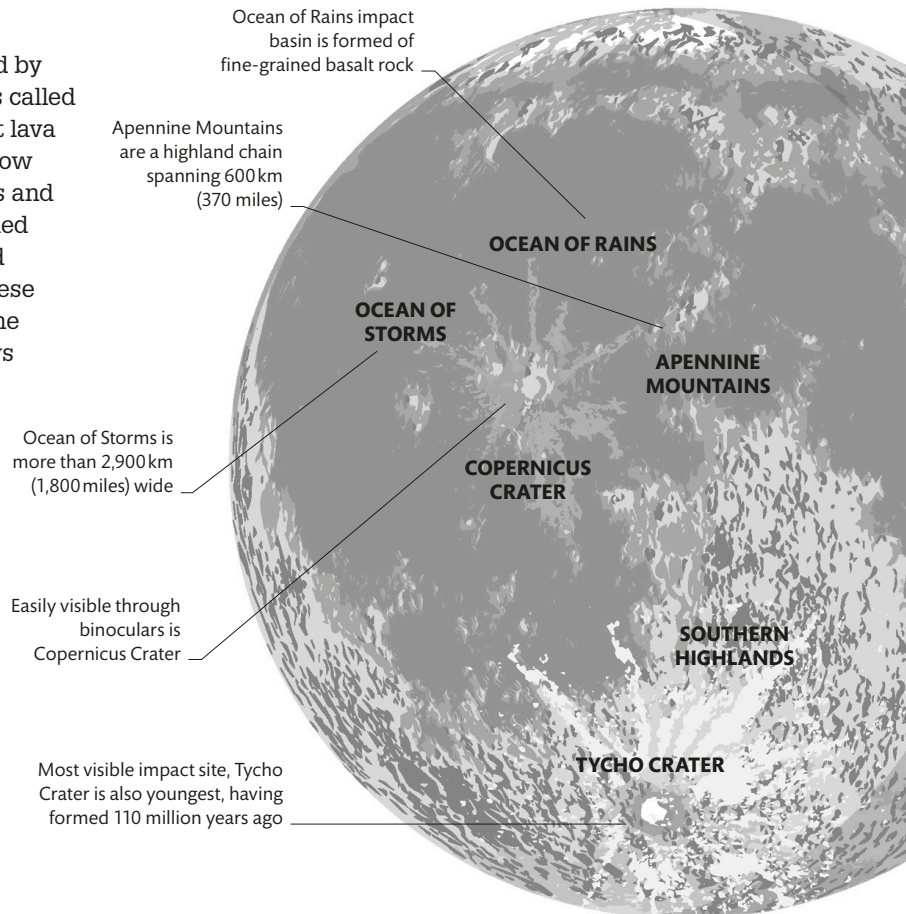
- 1 Collision course**
Another planet - Theia - approaches the early Earth from the outer Solar System at 14,000 kph (8,700 mph).

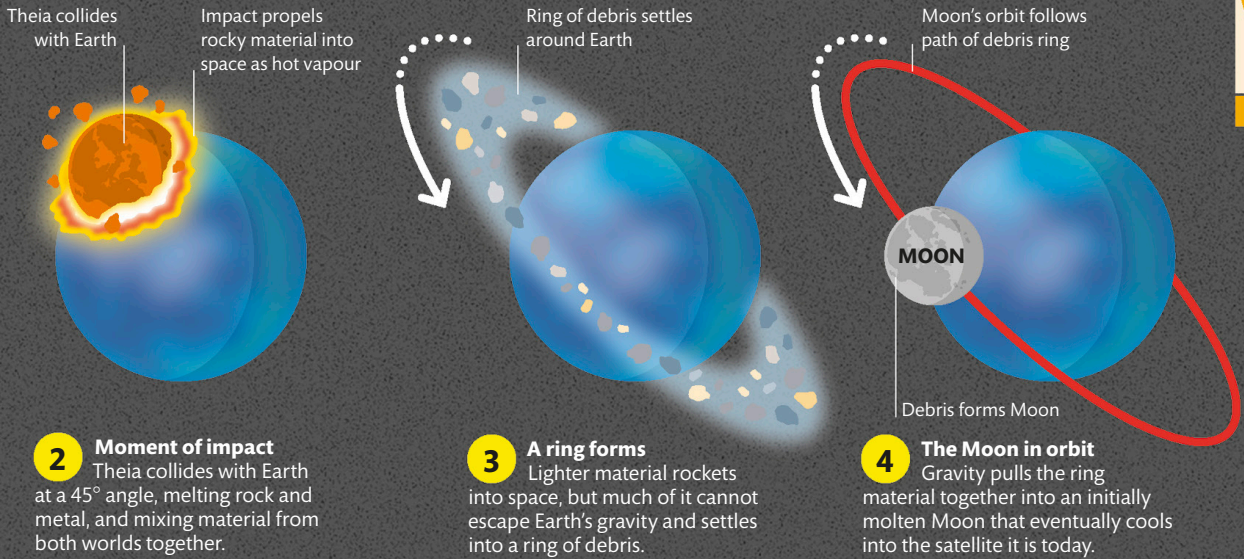
Surface features

The distinctive lunar surface is dominated by bright areas of highland and dark patches called maria (or seas). Maria are smooth, ancient lava plains from the Moon's early volcanism, now strewn with impact craters from asteroids and comets. The mountainous highlands formed as an ocean of molten material cooled and solidified around 4.5 billion years ago. These features can be seen at their best when the Moon is partially illuminated and shadows throw the surface into sharp relief.

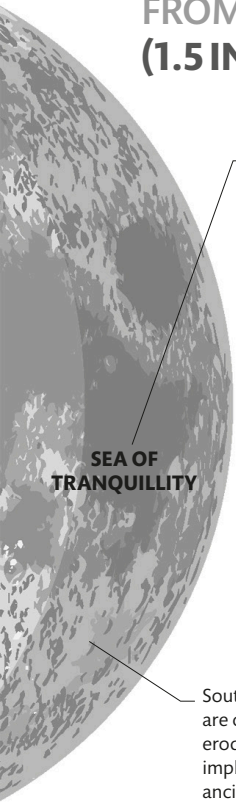
HOW MANY ASTRONAUTS HAVE WALKED ON THE MOON?

So far, a total of 12 astronauts have walked on the Moon. All travelled on NASA missions and stepped on the Moon between 1969 and 1972.



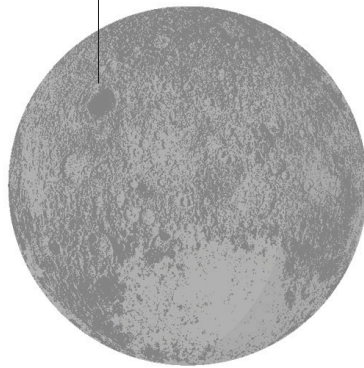


THE MOON MOVES AWAY FROM EARTH BY 3.8 CM (1.5 IN) EVERY YEAR



Sea of Tranquility is where Neil Armstrong first set foot in 1969

Less affected by early Earth's heat during formation, far side has fewer volcanic plains



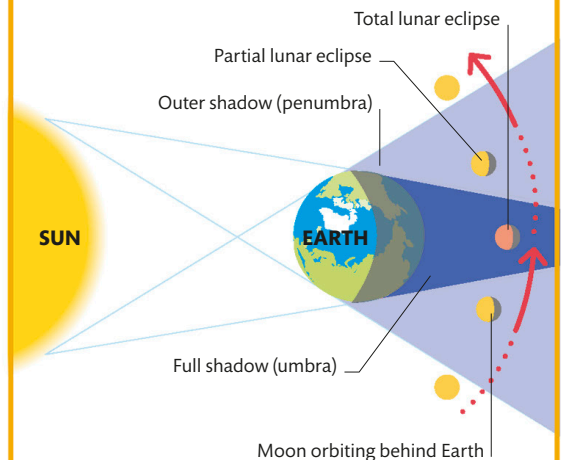
Southern highlands are covered in eroded craters, implying an ancient surface

The dark side of the Moon?

Contrary to popular belief, there is no permanently "dark side" of the Moon. The back of the Moon – properly called the "far side" – is not visible from Earth, but is often illuminated nonetheless.

LUNAR ECLIPSES

Lunar eclipses occur when the Moon enters the shadow of Earth. They are visible anywhere on Earth when the Moon is risen and usually appear at least twice per year. At total lunar eclipse, indirect sunlight, bent through Earth's atmosphere, turns the Moon an eerie red colour. Partial lunar eclipses are also possible when the Moon moves through Earth's outer, paler shadow.



Earth and the Moon

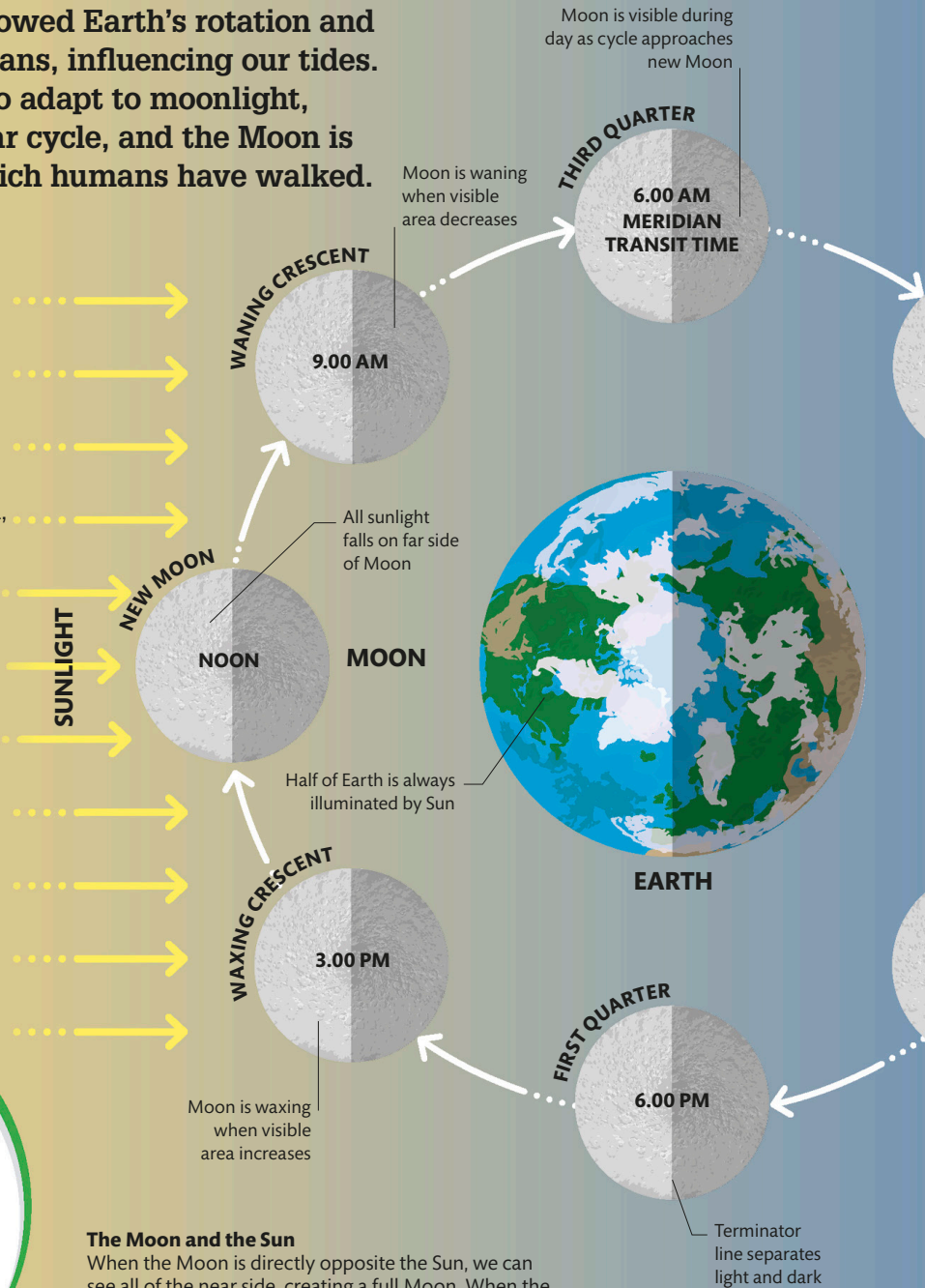
The Moon is the largest object in Earth's night sky. Its gravitational pull has slowed Earth's rotation and moves the water in our oceans, influencing our tides. Life on Earth has evolved to adapt to moonlight, tides, and the monthly lunar cycle, and the Moon is the only other world on which humans have walked.

Phases of the Moon

The Moon's changing appearance is one of the most striking features of the night sky, and its shifting shapes have been documented for millennia. Despite its apparent glow, the Moon generates no light of its own; instead, its surface reflects sunlight. Just like Earth, which at all times has one side in daylight and the other in night, the Moon is always half illuminated, but the portion that is visible from Earth changes as the Moon orbits. The lunar cycle lasts 29.5 days – slightly longer than the 27.3 days it takes for the Moon to orbit Earth. This is because Earth also moves during that time and it takes a little over two days for the Moon to realign with the Sun.

DOES THE MOON ROTATE?

The Moon rotates anti-clockwise and takes as long to spin on its axis as it does to orbit Earth. This is why the same side of the Moon is always visible from Earth.



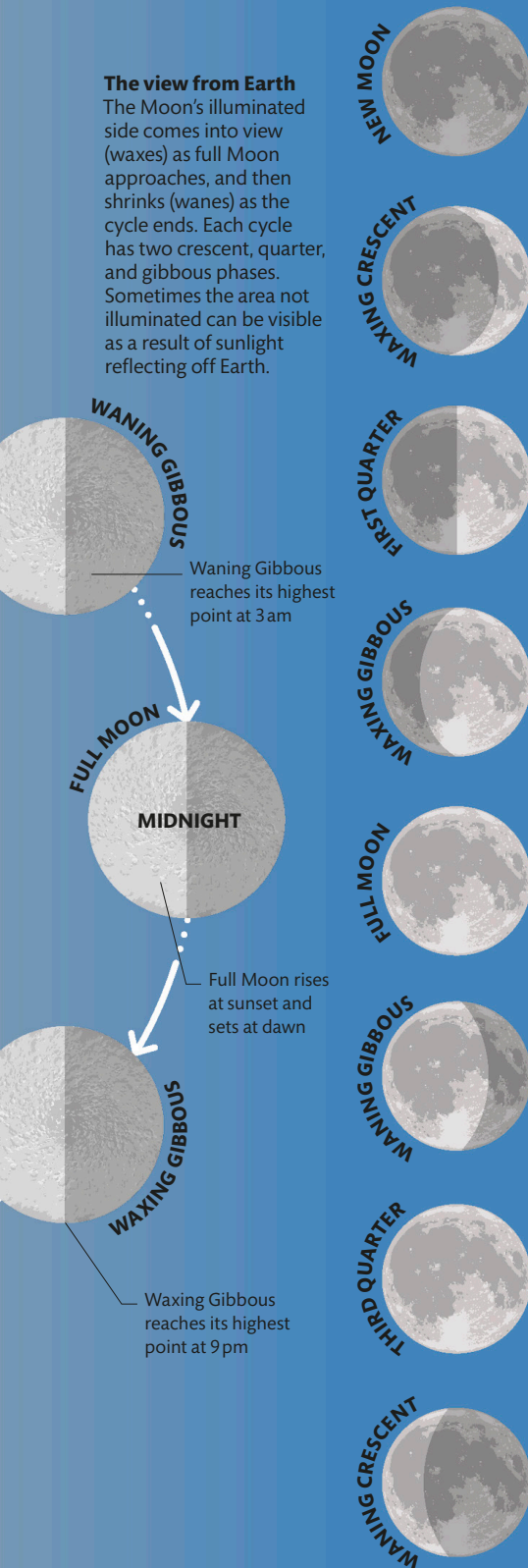
The Moon and the Sun

When the Moon is directly opposite the Sun, we can see all of the near side, creating a full Moon. When the Moon moves between Earth and the Sun, all light falls on the far side and we see a new Moon. The time that the Moon reaches its highest point in the sky (meridian transit) gradually changes through the cycle of phases.



The view from Earth

The Moon's illuminated side comes into view (waxes) as full Moon approaches, and then shrinks (wanes) as the cycle ends. Each cycle has two crescent, quarter, and gibbous phases. Sometimes the area not illuminated can be visible as a result of sunlight reflecting off Earth.

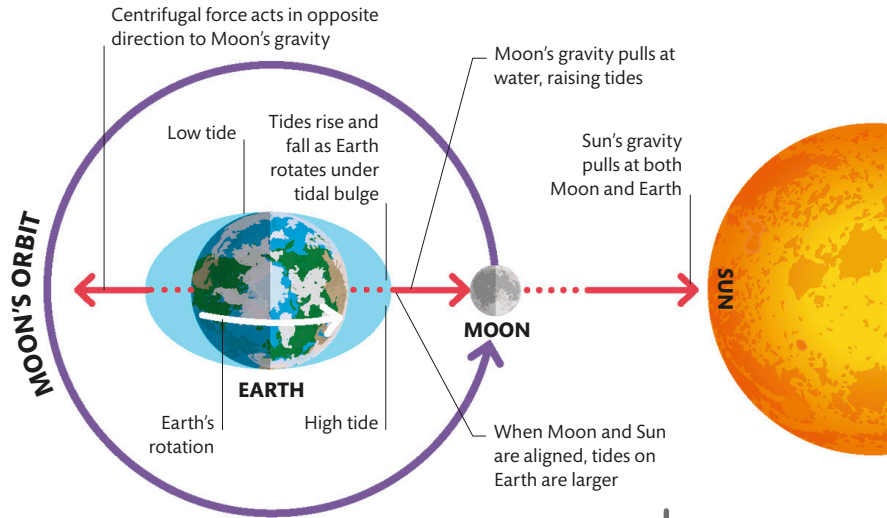


Tides

Most places on Earth experience two high tides and two low tides every day as the planet spins through four distinct regions. The gravitational pull of the Moon causes Earth's oceans to bulge, creating high tides. When the tide goes out, the rotation of Earth is causing the tidal bulge to move away from the shore.

Tidal forces

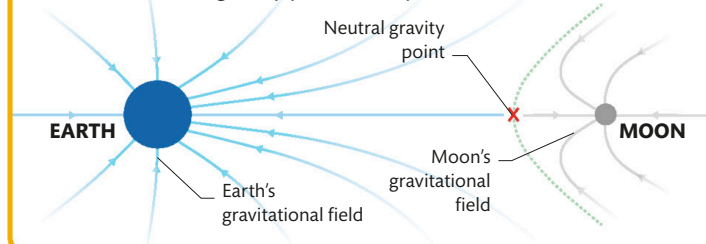
Sea levels rise when facing the Moon as lunar gravity pulls on the water. Water is also pulled away from other areas of Earth's ocean, creating low tides. A second area of high tide on Earth's far side is due to an outward centrifugal force that exceeds the inward gravitational pull.



THE MOON'S GRAVITY LENGTHENS EARTH'S DAY BY AN EXTRA HALF AN HOUR EVERY 100 MILLION YEARS

JOURNEY TO THE MOON

Six crewed spacecraft travelled a three-day flight path to the Moon between 1969 and 1972. At 70,000 km (43,500 miles) from the Moon, the spacecraft reached the neutral gravity point, where the Moon's gravity pulled the spacecraft into orbit.



Mercury

The closest planet to the Sun, Mercury takes just 88 days to complete one orbit and it has the most elliptical orbit of any planet. Mercury is also the smallest planet in the Solar System with a radius of 2,400 km (1,500 miles), making it just over a third of the size of Earth.

DOES MERCURY HAVE ANY MOONS?

No, Mercury's weak gravity and proximity to the Sun meant any would-be moon material was drawn into the Sun instead.

Basin is ringed by tall mountains

Volcanic plains cover 40 per cent of Mercury's surface

Impact crater Munch formed 3.9 billion years ago, long after Caloris Basin

Hollows inside craters carved out by solar winds

Smooth volcanic plains formed when early basin was flooded with lava

Mercury today has a dry, rocky surface

Streaks of material from powerful impacts surround craters

CALORIS BASIN

Craters hold material from original basin floor

Surface features

Mercury's surface is pockmarked with countless craters. Most of these scars, from the impacts of meteoroids, date from over 4 billion years ago. They have survived almost unchanged because Mercury is too small to have any significant atmosphere. As a result, Mercury's surface greatly resembles that of the Moon. In some places, smooth plains are criss-crossed with a series of folds, caused by the whole planet gradually contracting over time.

The Caloris Basin

Mercury has one of the Solar System's largest impact basins. At over 1,500 km (930 miles) across, the Caloris Basin is around 1.5 times the width of France and is surrounded by a ring of mountains 2 km (1.2 miles) high.

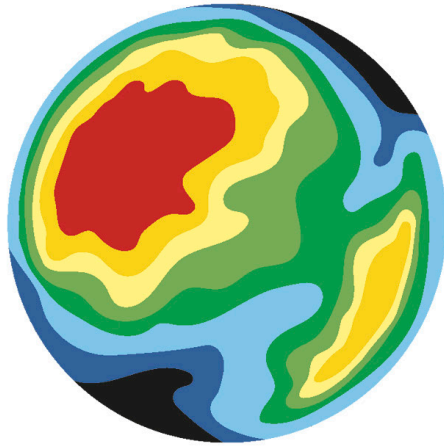
**MERCURY'S CRATERS ARE
NAMED AFTER ARTISTS,
INCLUDING DISNEY,
BEETHOVEN, AND VAN GOGH**





Atmosphere and temperature

Mercury cannot retain the significant amount of heat it receives from the Sun. During the day, the temperature climbs to over 400°C (750°F). Yet, without a thick atmosphere to trap that energy, the night side sees temperatures drop to -180°C (-300°F). This gives Mercury the biggest day-to-night temperature variation of any planet in the Solar System.



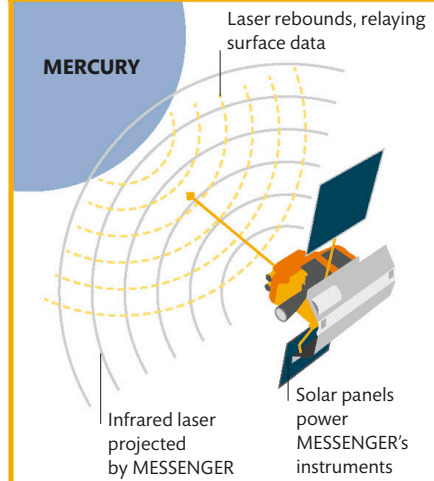
Temperature map

A map of variations in temperature below the surface of Mercury shows the hottest area (in red) directly below the Sun. This map uses observations taken with the Very Large Array (VLA) telescope in New Mexico, USA.

KEY



MESSENGER



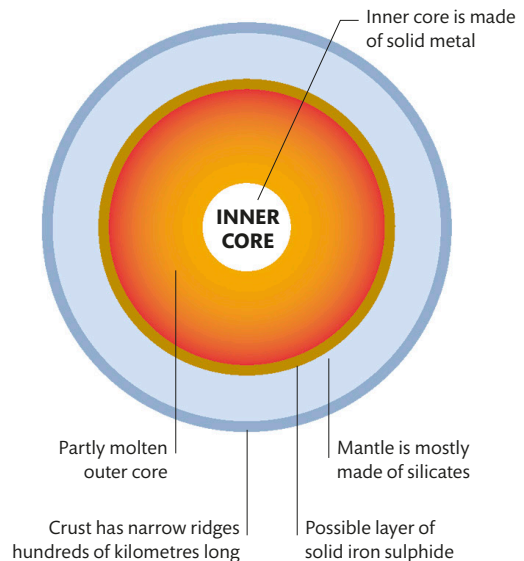
As Mercury has no moons, NASA's MESSENGER spacecraft is probably the only object to orbit the planet in its history. Entering orbit in 2011, MESSENGER mapped 99 per cent of Mercury's surface and used infrared laser signals to gather topographical data, before it was deliberately crashed into the planet in 2015.

Inside Mercury

Mercury is a dense planet made up of approximately 70 per cent metal and 30 per cent rock - only Earth has a higher density. An iron core (which may be partly molten) takes up more than half of the planet, and is surrounded by a 600-km- (370-mile-) wide mantle. At 30 km (20 miles) across, Mercury's rocky crust has a similar thickness to Earth's.

Space mission data

Data collected through space missions, including Mariner 10 and MESSENGER, has informed astronomers of Mercury's internal layers. MESSENGER also found evidence of water ice at Mercury's poles.



Venus

The second planet from the Sun is often referred to as Earth's twin, as it is only slightly smaller than Earth and has several familiar features, including mountains and volcanoes. However, Venus also has some unique structures.

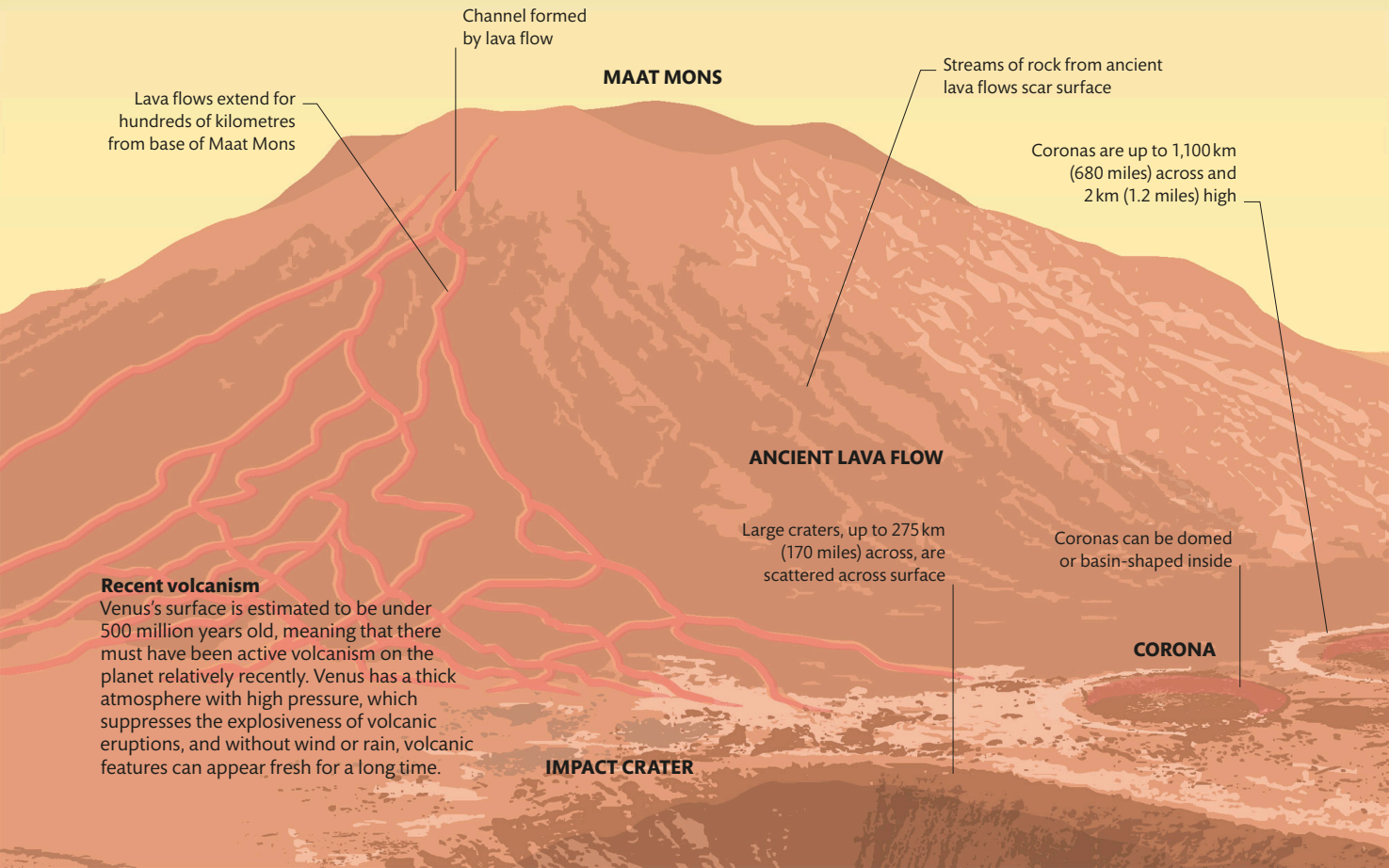
Surface features

The giant volcano known as Maat Mons towers 8 km (5 miles) above the surface of Venus. No other planet has more volcanoes, meaning that the Venusian surface is strewn with evidence of ancient lava flows and intense volcanic activity. Distinctive volcanic domes that resemble pancakes are scattered in clusters across the planet, as are deep impact craters from large meteorites. Raised, circular or oval structures hundreds of kilometres across also litter the surface. Called coronas, they were caused by hot magma welling up into the crust.

WHY DOES VENUS LOOK SO BRIGHT?

Venus appears to be bright when viewed from Earth because its atmosphere is filled with thick sulphuric acid clouds. Sunlight is reflected off these clouds, making it appear to shine.

**A DAY ON VENUS –
THE TIME FROM ONE
SUNRISE TO THE NEXT
– LASTS 117 EARTH DAYS**



Lava flows extend for hundreds of kilometres from base of Maat Mons

Channel formed by lava flow

MAAT MONS

Streams of rock from ancient lava flows scar surface

Coronas are up to 1,100 km (680 miles) across and 2 km (1.2 miles) high

ANCIENT LAVA FLOW

Large craters, up to 275 km (170 miles) across, are scattered across surface

Coronas can be domed or basin-shaped inside

CORONA

IMPACT CRATER

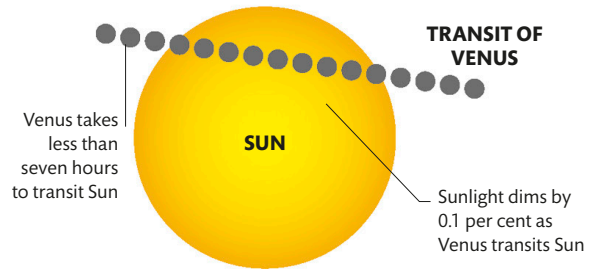
Recent volcanism

Venus's surface is estimated to be under 500 million years old, meaning that there must have been active volcanism on the planet relatively recently. Venus has a thick atmosphere with high pressure, which suppresses the explosiveness of volcanic eruptions, and without wind or rain, volcanic features can appear fresh for a long time.



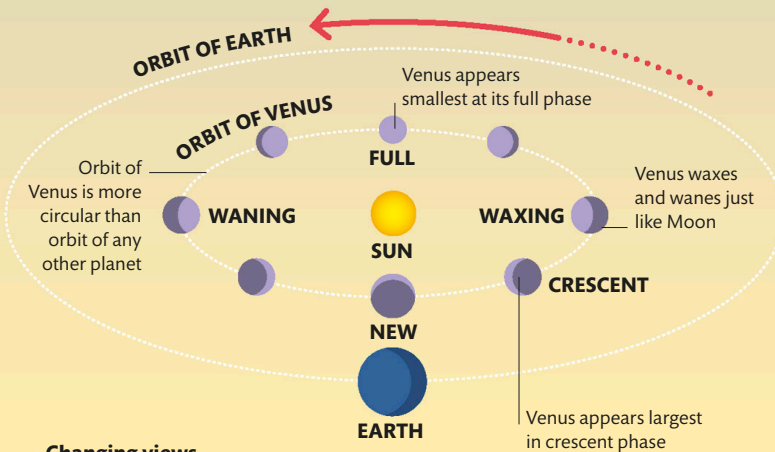
TRANSITS OF VENUS

Venus passes directly between Earth and the Sun in a rare event called a transit. Two transits of Venus occur over an eight-year period, but then it is more than a century before the next pair occur. The next transits will be in 2117 and 2125. The time it takes for Venus to transit the Sun was initially used to calculate the Earth–Sun distance, and transits are still invaluable to astronomers. Sunlight to Earth dims slightly during transits, and astronomers look for similar occurrences to identify Earth-sized planets orbiting nearby stars.



Phases of Venus

Italian astronomer Galileo Galilei spotted in 1610 that, like the Moon, Venus has phases, thus proving that all planets – including Earth – circle the Sun. As Venus orbits the Sun, its illumination viewed from Earth appears to change. Slivers of Venus appear to be bigger and brighter as it nears Earth, then as Venus passes behind the Sun a full hemisphere is visible. The cycle takes over two-and-a-half Venusian years (584 Earth days) to complete.

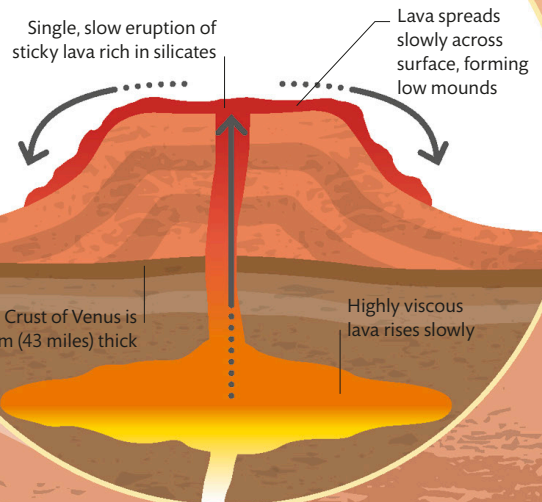


Changing views

When Venus is opposite the Sun, it appears on Earth to be fully lit up. When it is closest to Earth, most sunlight falls onto the far side of Venus, revealing only a sliver of the planet.

PANCAKE DOME FORMATION

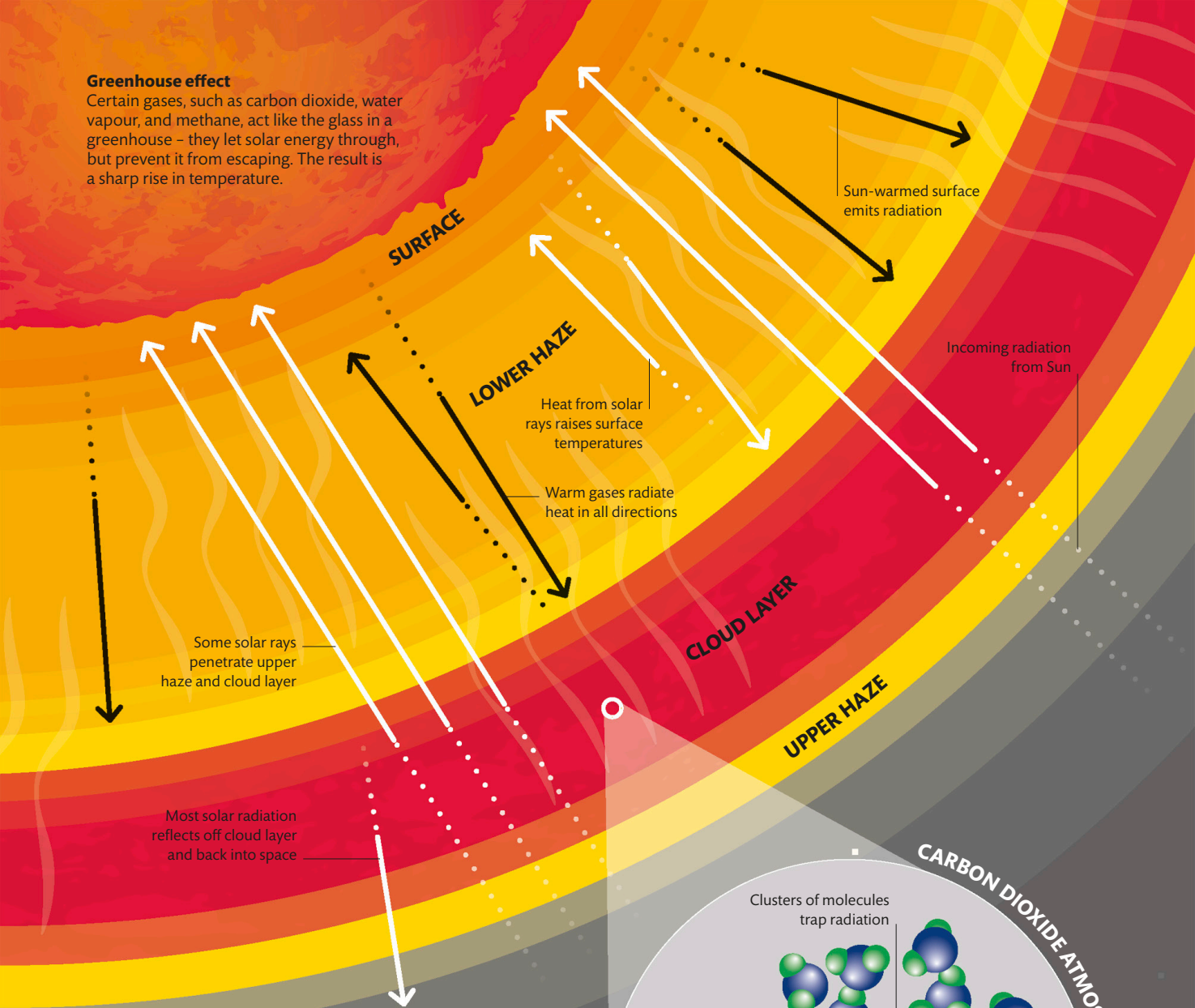
Flat volcanic structures, known as pancake domes, are unique to Venus. Thick, slow-moving lava rises through a central vent and spreads up to 100 times further than it does from similar structures on Earth.



PANCAKE DOME

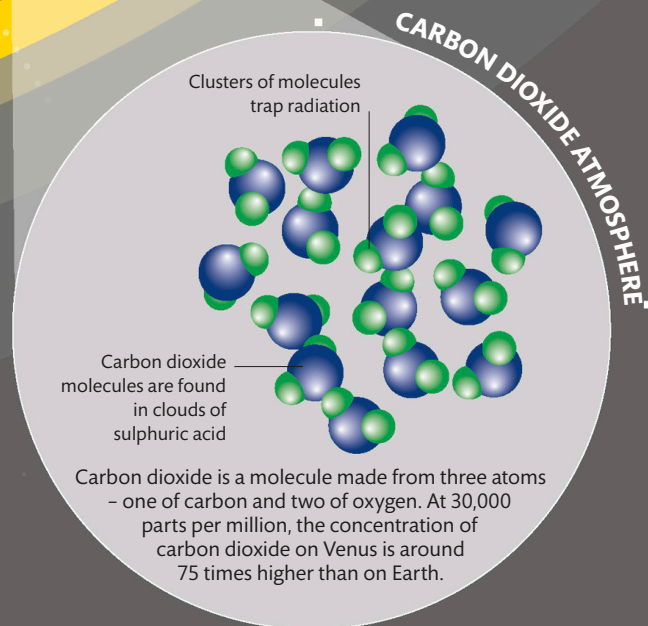
Greenhouse effect

Certain gases, such as carbon dioxide, water vapour, and methane, act like the glass in a greenhouse – they let solar energy through, but prevent it from escaping. The result is a sharp rise in temperature.



Runaway greenhouse effect

As we know from recent climate change on Earth, carbon dioxide has a potent warming effect. Water vapour is a powerful greenhouse gas too. Carbon dioxide and water vapour released by volcanic activity built up in Venus's atmosphere, which got hotter and hotter. As the water broke down or escaped, more carbon dioxide formed, warming the planet even further. Once this process had started, it could not stop and became a runaway effect.



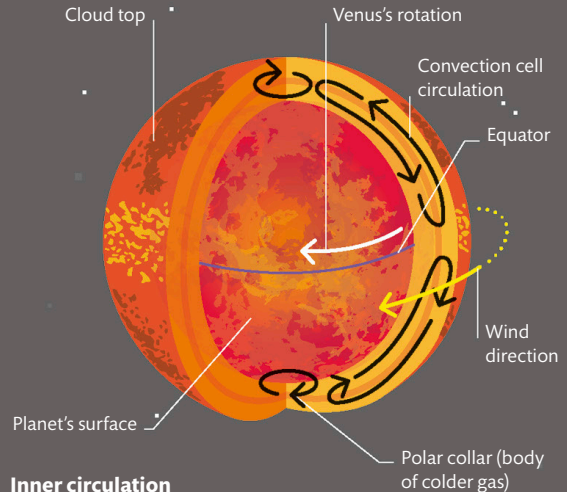


Hothouse planet

Our nearest planetary neighbour, Venus is the hottest planet in the Solar System and a sweltering greenhouselike world with an extreme climate.

Super-rotation

A quirk of Venus is that the time it takes to rotate relative to the stars is longer than its year of 225 Earth days. It also rotates in the opposite direction to the other planets. One full rotation takes 243 Earth days, although the solar day on Venus is shorter, lasting 117 days. Despite Venus's sluggish rotation, high-speed winds whip around the upper atmosphere over the equatorial region in just four days. This super-rotation is partly due to heat from the Sun causing variations in the atmospheric pressure, but the causes are not fully understood.



Inner circulation

Hot gas rises at the equator and flows towards the poles, where it cools and sinks back down to be reheated. These conveyor belts of gas circulating across Venus are called convection cells.

**STANDING ON VENUS
WOULD FEEL LIKE HAVING
15 ELEPHANTS ON
YOUR SHOULDERS**

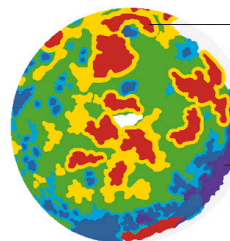


IS THERE LIFE ON VENUS?

There may be life on Venus, although there is no current evidence. Some scientists argue that life could persist in the cooler regions of the upper atmosphere.

DID VENUS HAVE WATER?

Venus may not have always been such a hostile environment. Billions of years ago, before the greenhouse effect, the planet may have been more Earthlike. Infrared mapping reveals lower-lying regions that may have contained shallow oceans.



Hotter areas show low altitudes of potential oceans

Slightly cooler, high altitudes may have been ancient continents

SOUTHERN HEMISPHERE

Structure and composition

With the exception of oceans, the surface of Mars has many similarities to the surface of Earth. Soaring mountain ranges, ice caps, towering volcanoes, and long, deep valley systems can all be seen on Mars. Far below the surface sits a core that is roughly 2,100 km (1,300 miles) in radius and is formed of mostly iron and nickel, although there is a small amount of sulphur too. There is also evidence from magnetized areas of the crust that Mars once had a magnetic field, but without a molten core it faded away.

Olympus Mons is Mars's largest volcano

The surface of Mars

Mars's surface is strikingly varied, with non-volcanic low-lying regions dominating the surface north of the equator, and highlands and extinct volcanoes concentrated in the southern hemisphere.

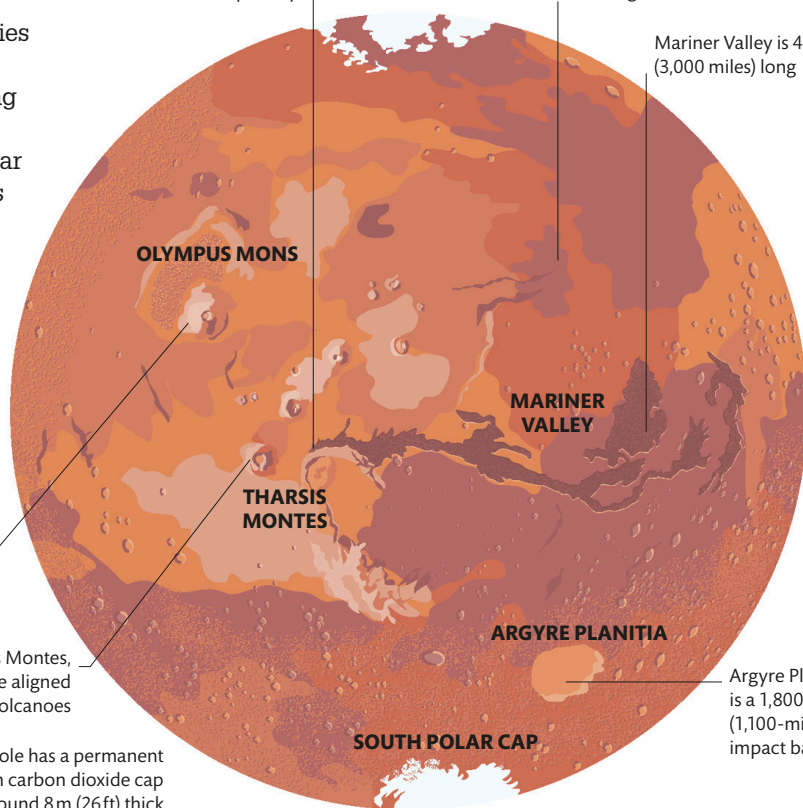
Tharsis Montes, three aligned volcanoes

South pole has a permanent frozen carbon dioxide cap around 8 m (26 ft) thick

Noctis Labyrinthus is a region criss-crossed with deep valleys

Chryse Planitia is site of Viking 1 lander

Mariner Valley is 4,800 km (3,000 miles) long



Argyre Planitia is a 1,800-km- (1,100-mile-) wide impact basin

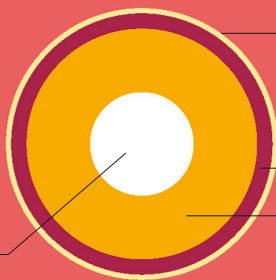
Mars

No other planet has captured the human imagination quite like Mars, the fourth planet from the Sun. The Red Planet continues to attract daring rover missions to explore its desertlike surface.

Internal structure

Around Mars's dense core is a thick, rocky mantle, a crust, and a thin atmosphere of carbon dioxide, nitrogen, and argon. Mars is still seismically active and has hundreds of "Marsquakes" each year.

Dense core may be partly liquid



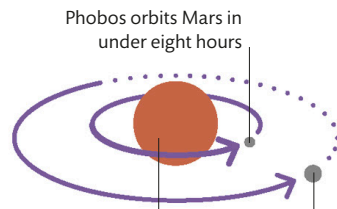
Thin atmosphere provides little protection

Thin crust of dust-covered volcanic rock

Mantle of silicate rock

MARS'S MOONS

Mars has two moons that are much smaller than the major satellites of other planets. The moons could have formed from material thrown into Mars's orbit by impacts or have once been asteroids from the neighbouring Main Belt.



Phobos's quick orbit means it rises and sets twice per Martian day

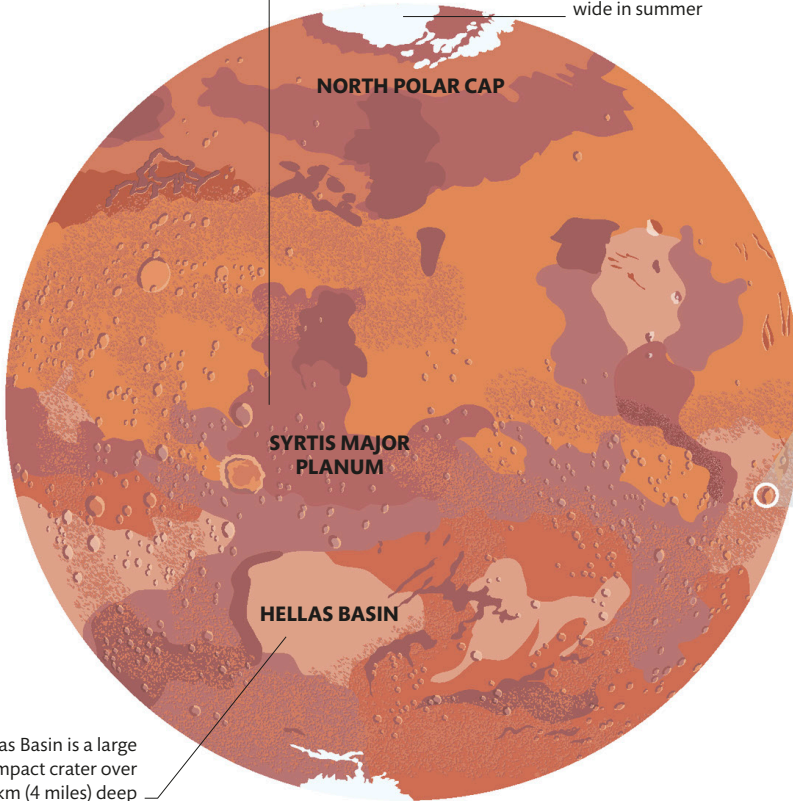
Deimos has a slower 32-hour orbit



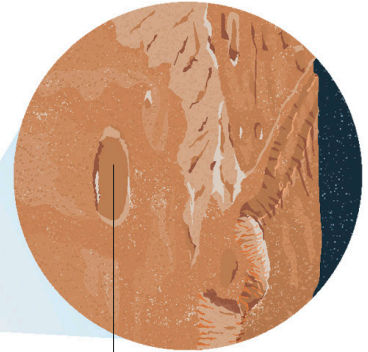
Syrtis Major Planum, a low shield volcano, is so prominent it was first permanent feature seen from Earth

North polar ice cap is 1,000 km (600 miles) wide in summer

MARS'S RED COLOUR COMES FROM IRON OXIDE (RUST)



Hellas Basin is a large round impact crater over 7 km (4 miles) deep



Gusev Crater once held water or water ice from a nearby channel

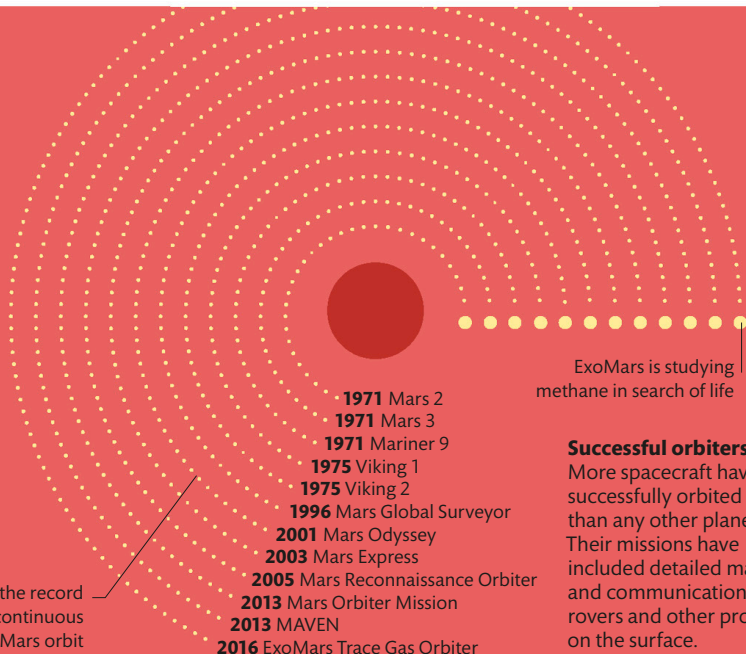
Spirit landing site

In 2004, NASA's Spirit rover landed on an ancient lake bed called Gusev Crater. Spirit spent 1,944 days exploring the area before it became stuck in the crater's soft sand.

The search for life

Of all the planets in the Solar System, Mars is most likely to have supported life in its past. It is thought that the Red Planet had a much wetter past, with oceans and lakes sprawled across its surface and ancient rivers meandering across the Martian terrain. As every living thing on Earth requires liquid water to survive, its presence on Mars suggests life might also have gained a foothold when the climate was more favourable. Scientists are searching for signs of biological activity and even question whether life could exist on Mars in the future.

Mars Odyssey holds the record for the longest continuous service in Mars orbit



- 1971 Mars 2
- 1971 Mars 3
- 1971 Mariner 9
- 1975 Viking 1
- 1975 Viking 2
- 1996 Mars Global Surveyor
- 2001 Mars Odyssey
- 2003 Mars Express
- 2005 Mars Reconnaissance Orbiter
- 2013 Mars Orbiter Mission
- 2013 MAVEN
- 2016 ExoMars Trace Gas Orbiter

ExoMars is studying methane in search of life

Successful orbiters

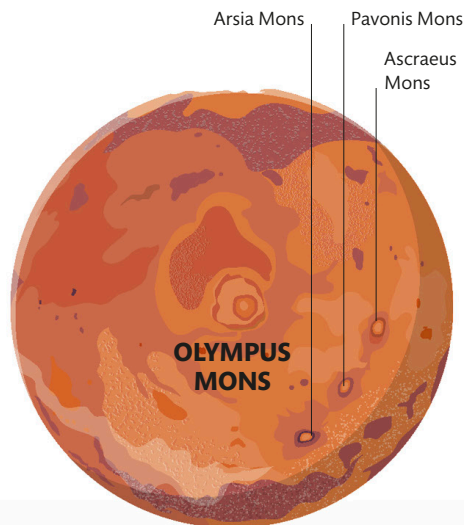
More spacecraft have successfully orbited Mars than any other planet. Their missions have included detailed mapping and communication with rovers and other probes on the surface.

Martian ice and volcanoes

Two of the most conspicuous features on the surface of Mars are its ice caps and volcanoes. Together they hold many secrets of Mars's past and have been heavily scrutinized by scientists.

Volcanoes

One region of Mars is synonymous with volcanoes – the Tharsis Bulge. Straddling the Martian equator to the west of the Mariner Valley, the Tharsis Bulge is a volcanic plateau formed by the upwelling of more than a billion billion tonnes of material from inside Mars. It is so massive, it may have affected the tilt of Mars's rotation axis. On or close to the bulge sit four large volcanoes, including the colossal Olympus Mons, all of which are taller than Mount Everest on Earth.



THARSIS BULGE FROM ABOVE

Olympus Mons

Mars's tallest summit is also the Solar System's highest volcanic peak. Olympus Mons is so sprawling it covers an area of 300,000 square km (116,000 square miles), approximately the same size as Italy. It is also relatively shallow, with an average incline of just 5°.

ROCK GLACIER

Over a thousand glaciers have been identified on Mars in bands that sit halfway between the equator and the poles, including inside Olympus Mons. These slow-moving rivers of frozen soil (permafrost) are hidden under a thick layer of surface dust called regolith.

REGOLITH

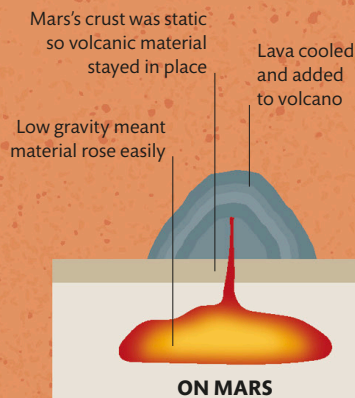
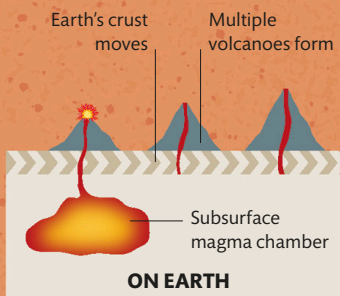
PERMAFROST

CARBONATE ROCKS

Olympus Mons is 500km (300 miles) across, the width of US state of Arizona

How did Martian volcanoes form?

Mars's gravity is 2.5 times weaker than Earth's, so volcanic structures could grow taller. Unlike on Earth, the surface of Mars does not shift around, so volcanic eruptions were concentrated in the same area.

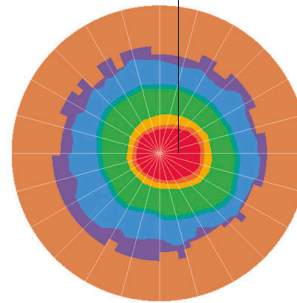




Water and ice

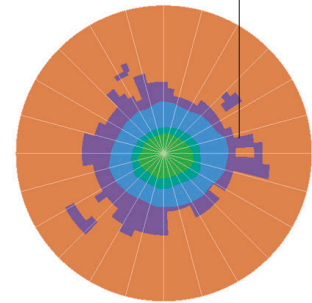
Mars is book-ended by two vast polar ice caps, which grow and shrink with the seasons and are around 3 km (2 miles) thick. If all the ice melted, the liquid would flood Mars to a depth of over 5 m (16 ft). The ice caps contain water and frozen carbon dioxide that turns into a gas at warmer temperatures. This seasonal release of gas causes fierce winds to blow dust around the planet. Ice has also been spotted beneath the surface further from the poles, scuffed up by the wheels of trundling Mars rovers.

High concentrations of carbon dioxide ice



EARLY SPRING

Carbon dioxide ice recedes as Mars warms

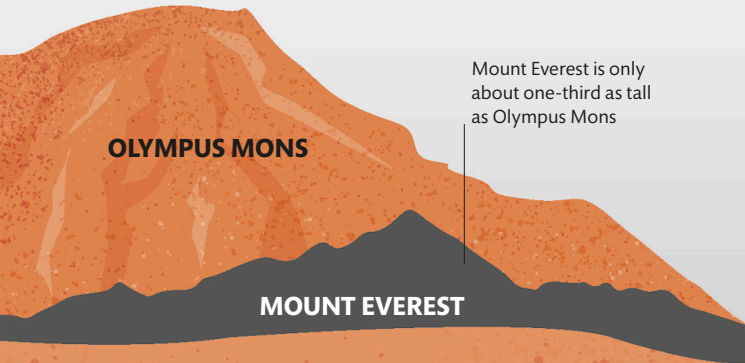
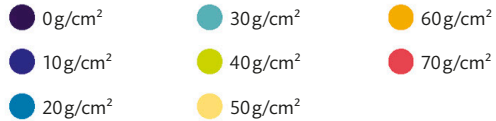


LATE SPRING

THE WATER IN MARTIAN ICE COULD COVER THE PLANET WITH OCEANS 35 M (115 FT) DEEP



KEY TO ICE DEPTH (MEASURED BY PRESSURE)



Mount Everest is only about one-third as tall as Olympus Mons

OLYMPUS MONS

MOUNT EVEREST

ARE MARS'S VOLCANOES STILL ACTIVE?

Most scientists think not, but some argue that the volcanoes are dormant. Liquid water found deep under the surface might have been thawed by magma chambers.

THE MARINER VALLEY



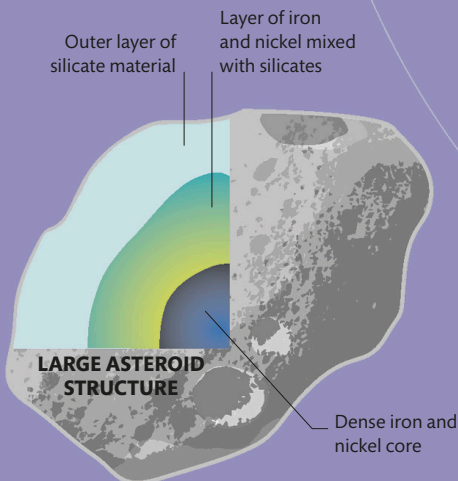
At over 4,000 km (2,500 miles) long and 8 km (5 miles) deep, the gigantic and intricate system of the Mariner Valley cuts a quarter of the way around the Martian equator. The huge volcanic crack in Mars's crust formed 3.5 billion years ago as the planet cooled. It is named after the Mariner 9 spacecraft, which spotted it while orbiting the Red Planet in the early 1970s.

Asteroids

There is more to the Solar System than the Sun, its planets, and their moons. Small lumps of rock and metal called asteroids are littered between the planets in orbits around the Sun.

Asteroids and the early Solar System

Asteroids appear in the sky as starlike specks of light, but they are in fact rocky and metallic objects orbiting the Sun. They are the leftover building blocks of the Solar System and as such predate the planets. That makes asteroids invaluable tools for understanding the formation of the Solar System. The meteorites that periodically land on Earth are mostly fragments of asteroids. By analysing their radioactive impurities, scientists can estimate their age and, in turn, the age of the Solar System.



What is an asteroid?

Formed of materials such as silicates, nickel, and iron, fused together and impacted by collisions, asteroids are small orbiting bodies. The largest asteroid, Ceres, is almost 950 km (590 miles) across and is also classed as a dwarf planet.

Near-Earth asteroid
Toutatis has an
unusual elongated
orbit that takes four
years to complete

Gaspra was first
asteroid to be visited
by a spacecraft

Itokawa orbits very close
to Earth every two years

Eros, first near-Earth asteroid
discovered, has short orbit of
less than two years

MARS

MERCURY

SUN

VENUS

EARTH

HOW MANY NEAR-EARTH ASTEROIDS ARE THERE?

There are over 20,000 near-Earth asteroids known to move in the vicinity of our planet. Scientists are developing ways to stop any potentially dangerous collisions with Earth.

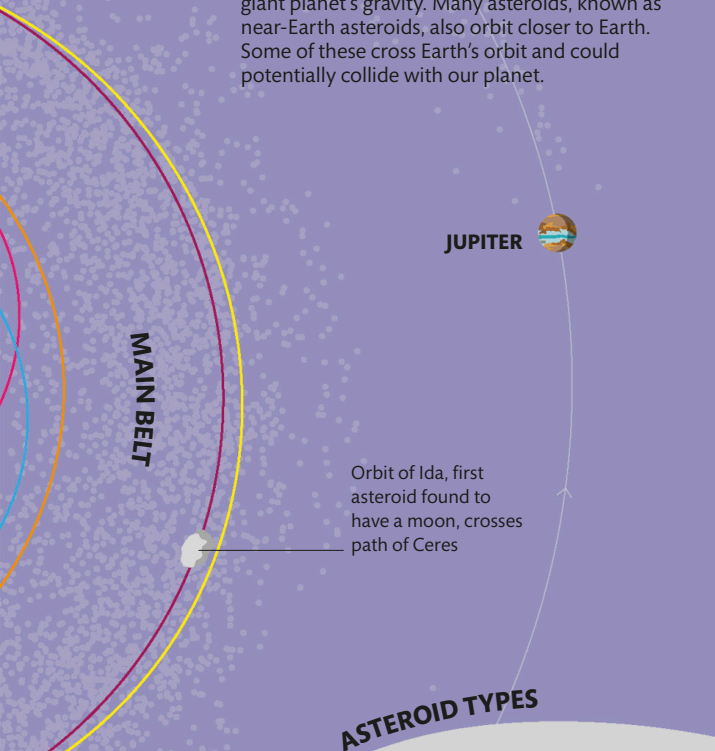
Ceres was studied from
orbit by Dawn spacecraft

TROJAN ASTEROIDS



Asteroids in the Solar System

Ninety per cent of asteroids are found in the Main Belt, also known as the Asteroid Belt, between the orbits of Mars and Jupiter. Smaller clusters of asteroids, called Trojan asteroids, trail Jupiter's path around the Sun, trapped by the giant planet's gravity. Many asteroids, known as near-Earth asteroids, also orbit closer to Earth. Some of these cross Earth's orbit and could potentially collide with our planet.



Types of asteroid

There are three main types of asteroid, grouped by their characteristics.

Si

Silicon

Fe

Iron

Mg

Magnesium

S-Type

This moderately bright type is made of silicate rocks and metals, with hardly any water.

C

Carbon

P

Phosphorus

N

Nitrogen

C-Type

A very dark type made of rocks and clay minerals, with high carbon content and hardly any metals.

Fe

Iron

Ni

Nickel

M-Type

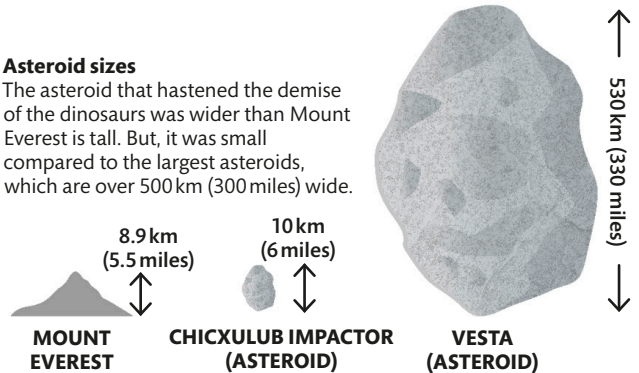
A moderately bright type with high metal content, made of rock and water containing minerals.

Extinction-level events

Asteroids that collide with Earth can cause death and destruction. Sixty-six million years ago an asteroid the size of a small city, the Chicxulub Impactor asteroid, careened into the coast of Mexico at Chicxulub, triggering an apocalyptic event that wiped the dinosaurs from the world. Similarly sized events strike approximately every 100 million years.

Asteroid sizes

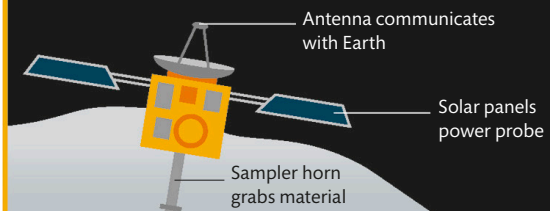
The asteroid that hastened the demise of the dinosaurs was wider than Mount Everest is tall. But, it was small compared to the largest asteroids, which are over 500 km (300 miles) wide.



**THE COMBINED MASS OF ALL
THE ASTEROIDS IS JUST THREE
PER CENT OF THE MASS
OF THE MOON**

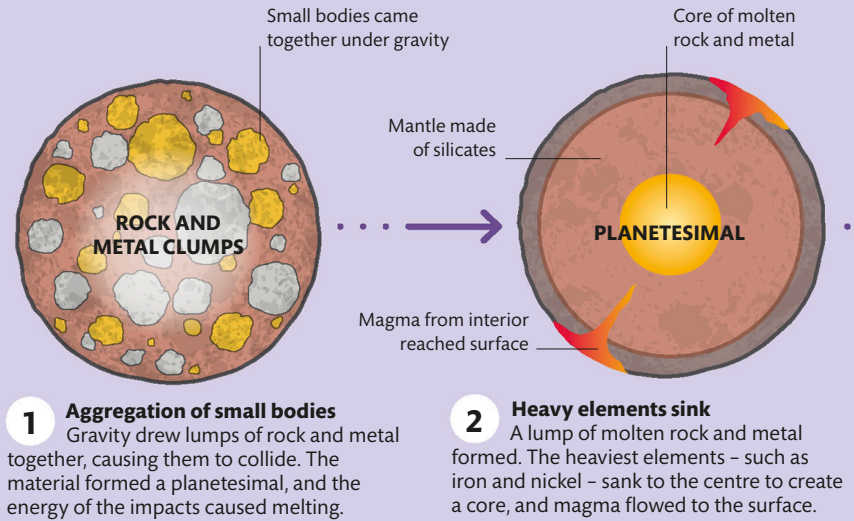
GRABBING AN ASTEROID

Rather than waiting for meteorites to deliver asteroid samples to Earth, the Japanese space agency (JAXA) dispatched the Hayabusa probe to land on the asteroid Itokawa in 2005. It grabbed 1,500 dust particles to inform our understanding of the asteroid's formation, before returning to Earth and landing in the Australian Outback.



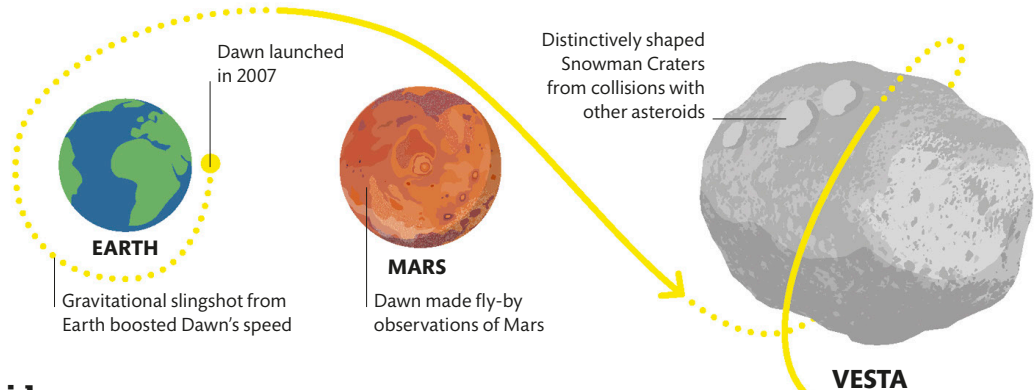
How Vesta formed

Asteroids, also known as minor planets, are leftover building blocks of planets. The planets started to grow when gravity attracted small pieces of material together to make chunks called planetesimals. Not all of the pieces were incorporated into planets, and a belt was left between Mars and Jupiter. However, some of the most massive, such as Vesta, grew hot enough to melt and were rounded by their own gravity. Smaller planetesimals kept their irregular shapes.



Exploring asteroids

To learn more about asteroids and the Main Belt, scientists study them with instruments, such as the Hubble Space Telescope, and dispatch spacecraft, such as NASA's Dawn, to make detailed observations and return material to Earth.



Differing asteroids

Ceres and Vesta are neighbours in the Main Belt, but they are not alike. Vesta is the smaller of the two, at 570 km (355 miles) across to Ceres's 950 km (590 miles). Vesta is also closer to the Sun, and it is dense and rocky like the terrestrial planets. In fact, it is thought Earth was made from bodies like Vesta colliding. Ceres's additional distance from the Sun means it is cold enough to retain water ice, making its structure more like some of the icy moons of the outer Solar System.

Ceres and Vesta

There are over a million asteroids in the Main Belt (see pp.60–61), but just two account for 40 per cent of their combined mass – Ceres, which is also classified as a dwarf planet, and Vesta.

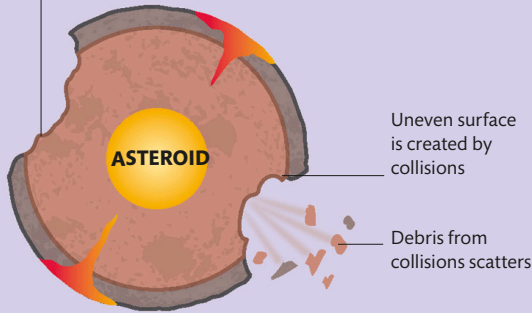
Dawn reached top speed of 41,000 kph (25,000 mph)

COULD THERE BE LIFE ON CERES?

Ceres is a good place to search for potential signs of life. It has water and possibly a hot core. However, if there are any signs of life, it is likely to have been in Ceres's distant past.



Mantle visible after crust breaks off

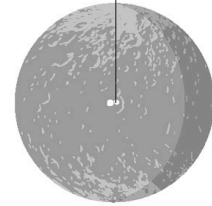


- 3 Impact breaks off fragments**
Later collisions chipped away at the solidified surface, further contributing to an uneven shape. Particularly big impacts exposed deep-lying inner layers.

WHITE SPOTS ON CERES

As NASA's Dawn approached Ceres in 2015, it saw bright spots on the floor of the Occator Crater. They appear to be highly reflective salty deposits, possibly left behind when water evaporated away from Ceres and into space. Astronomers suspect there is a deep reservoir of salty water inside Ceres that periodically reaches the surface.

White spots apparent on surface



CERES

Radio signals transmitted information back to Earth

Gamma ray and neutron detector measured elemental composition

Dawn mapped surface in visible and infrared light

Inside Ceres

Ceres may have a deep mantle of water-bearing rocks, an outer crust of ice and minerals with salty deposits, and a layer in between containing some salty liquid. There could be more water in Ceres than on Earth.

ROCKY MANTLE
LIQUID BRINE
ICY CRUST

Ceres is covered in many small craters

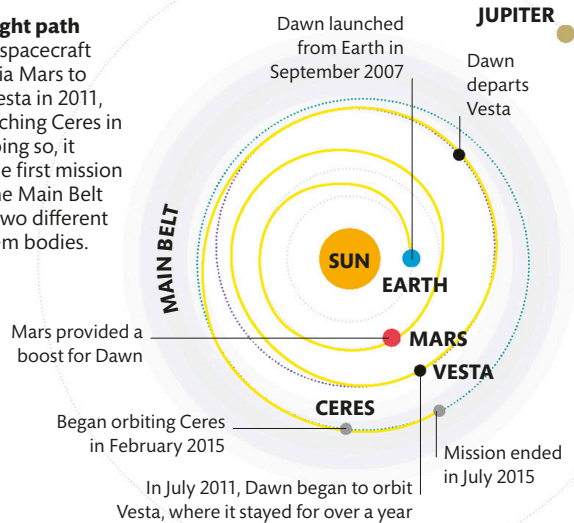
CERES

NASA's Dawn mission

NASA's Dawn mission studied Ceres and Vesta in order to reveal clues about the beginning of the Solar System. Instruments on board were designed to work out the asteroids' compositions and help explain the evolutionary paths that made them so different. The mission also demonstrated the power of an ion engine (see pp.192–93).

Dawn's flight path

The Dawn spacecraft travelled via Mars to arrive at Vesta in 2011, before reaching Ceres in 2015. In doing so, it became the first mission to reach the Main Belt and orbit two different Solar System bodies.



VESTA'S RHEASILVIA CRATER
CONTAINS THE TALLEST
MOUNTAIN IN THE SOLAR SYSTEM

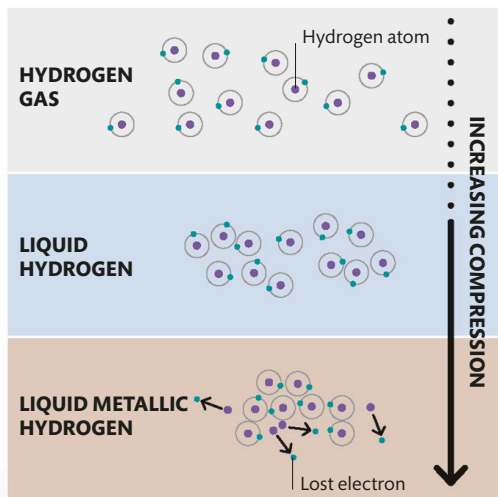


Jupiter

Jupiter is so big that all of the other planets in the Solar System could fit inside it. This gas giant, with its strong gravitational pull, dominates everything around it.

Internal layers

Jupiter has a radius of almost 70 million km (43 million miles), and its gargantuan size puts its internal layers under extreme pressure from the weight of material above. The planet is mostly made of hydrogen and helium. In the outer layer, these elements are gases, but deeper inside Jupiter, the gases are gradually crushed and become liquid. At around 20,000 km (12,000 miles) deep, they become an electrically charged liquid called metallic hydrogen. This layer forms the largest ocean in the Solar System. Beneath it is probably a hot core with a temperature of around 50,000°C (90,000°F).

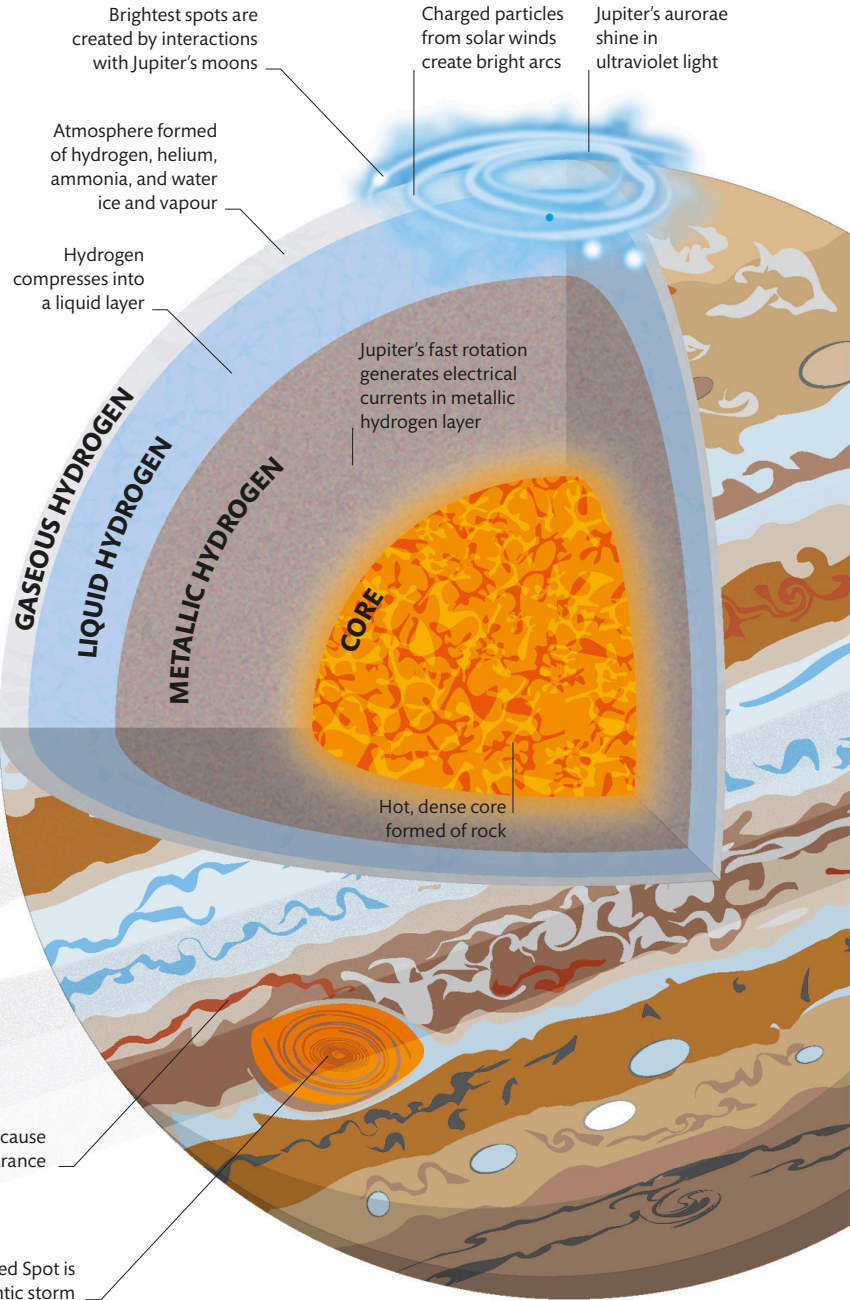


Compressed layers

As pressure increases, hydrogen atoms are pressed together, becoming liquid and eventually losing electrons. This makes the liquid electrically charged and metallic, which means it can conduct electric currents and generate magnetic fields.

Auroral ovals

Electric energy at Jupiter's poles causes auroral ovals 1,000 km (600 miles) wide. In these ovals, bright spots appear where Jupiter's magnetosphere draws charged particles from nearby moons.



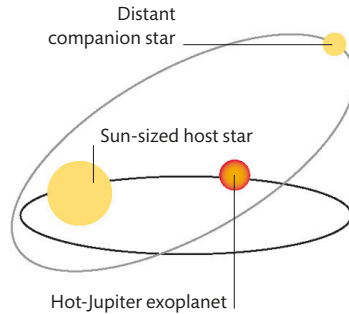


DOES JUPITER HAVE RINGS?

Yes, like the other three giant planets, Jupiter has rings. The rings are made from dust and are hard to see from Earth. They were spotted in 1979 by the Voyager 1 spacecraft.

HOT-JUPITERS

Astronomers have found many Jupiter-sized exoplanets close to other stars. These hot-Jupiters (see pp.102–103) orbit their host stars in under 10 days. It is thought that they formed further away from their host stars and migrated inwards over time, possibly pulled by the gravity of a companion star orbiting the host star.



Jupiter is surrounded by four rings

Rings are formed of small, dark dust particles

RINGS

Giant planet

Jupiter is so large that Earth could fit inside it more than 1,000 times. It has a bulge at the equator with flattened poles, caused by Jupiter's swift rotation.

JUPITER HAS THE SHORTEST DAY IN THE SOLAR SYSTEM AT 9 HOURS AND 56 MINUTES



Magnetosphere

Jupiter has a magnetic field so big that it extends up to 3 million km (2 million miles) towards the Sun, and the magnetotail behind Jupiter is more than 1 billion km (600 million miles) long, stretching out beyond Saturn's orbit. The magnetosphere's colossal size is a result of the huge convective currents generated inside Jupiter's subsurface ocean of metallic hydrogen.

Powerful field

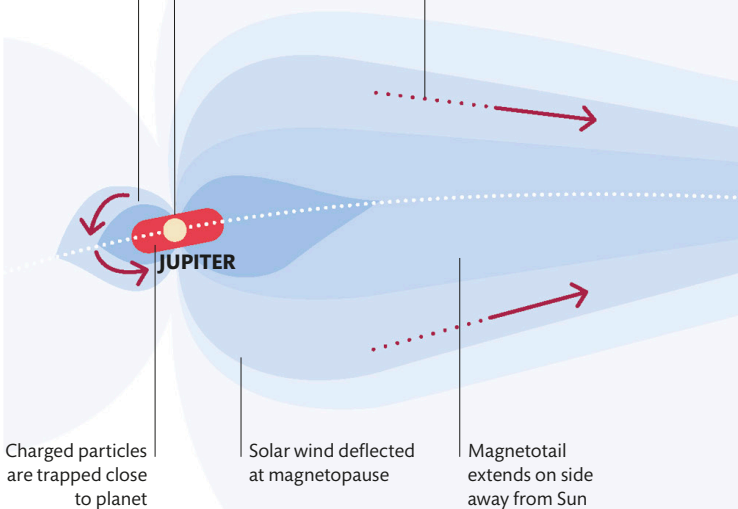
Jupiter's magnetic field is up to 54 times more powerful than Earth's magnetic field. It traps charged particles and accelerates their movement to incredibly high speeds.

Clouds mainly made of ammonia ice

Magnetic field wraps around side facing Sun

Charged particles funnel towards magnetic poles

Magnetic field sweeps solar wind away from Jupiter



Charged particles are trapped close to planet

Solar wind deflected at magnetopause

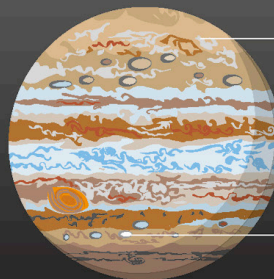
Magnetotail extends on side away from Sun

The Great Red Spot

The giant oval storm in Jupiter's southern hemisphere, the Great Red Spot, is the planet's most distinctive feature. It is a colossal anticyclone and the biggest storm in the Solar System. It has been observed since at least the 1830s, and in that time it has halved in size, although it is not known why. It is now about the same size as Earth and could become circular by 2040.

Storms on Jupiter

White oval storms are some of the most common types of storm seen on Jupiter. In December 2019 NASA's Juno spacecraft watched as two ovals merged together over several days.



Near north pole, a large cold spot is linked to Jupiter's aurorae

Row of white spots known as String of Pearls

Energy release

The Great Red Spot consists of rotating clouds with eddies joining at its edges. The region above the spot is hotter than any other part of Jupiter's atmosphere. It is thought that this is due to the storm compressing and heating gases. The heat energy is then transferred upwards.

Hot gases rise from storm

Spot is constantly changing, with material entering and exiting

HOW STRONG ARE THE WINDS ON JUPITER?

Surface winds on Jupiter can blow at over 600 kph (370 mph). It is thought that these winds are driven by convection deep inside Jupiter's hot interior.

Eddies crash together at base of storm, transferring energy

Eddies join together, feeding storm with energy

Without a solid surface, there is less friction to slow storm

HEATED ATMOSPHERE

Cooler gases in atmosphere sink

Rising energy heats atmosphere above spot

ENERGY TRANSFER

Gases are spun together by planet's spin

GREAT RED SPOT

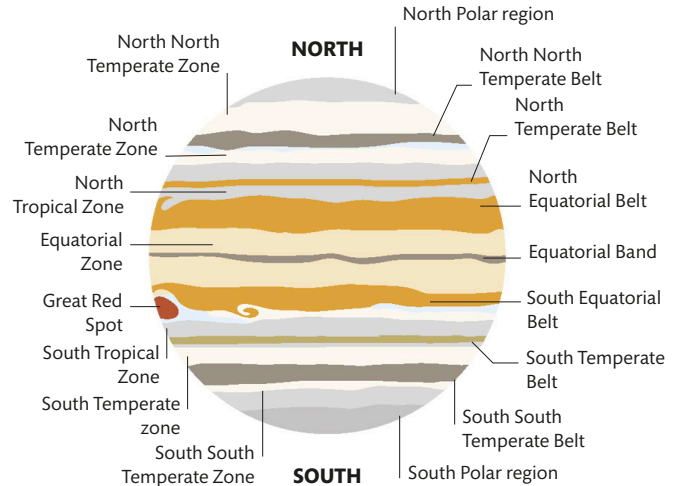


Jupiter's weather

No other planet has weather quite like Jupiter's. Its atmosphere churns with colossal storms and is riddled with lightning, both more powerful than anything experienced on Earth.

Cloud layers

Jupiter's visible surface is striped with orange, red, brown, and white clouds. Cyclones press together at Jupiter's poles, and eddies and whirlpools swirl around the planet, some spinning against Jupiter's rotation and persisting for centuries. The upper layers of Jupiter's clouds are laced with white ammonia ice and are organized into stripes called zones, which sit parallel to the planet's equator. Where these clouds are absent, deeper layers of the Jovian atmosphere are exposed, resulting in darker bands called belts.



Zones and belts

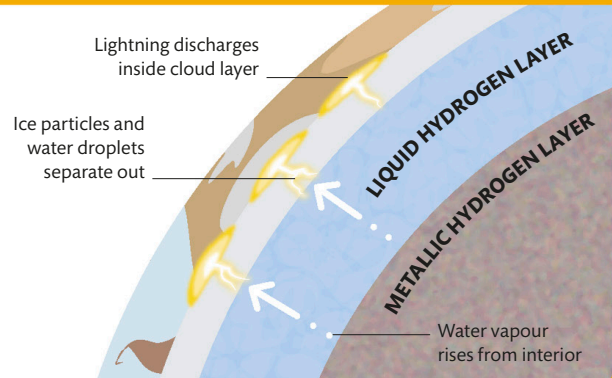
The weather on Jupiter is driven by convection, with hot gas rising within the white zones and cooler gas falling in the darker belts.

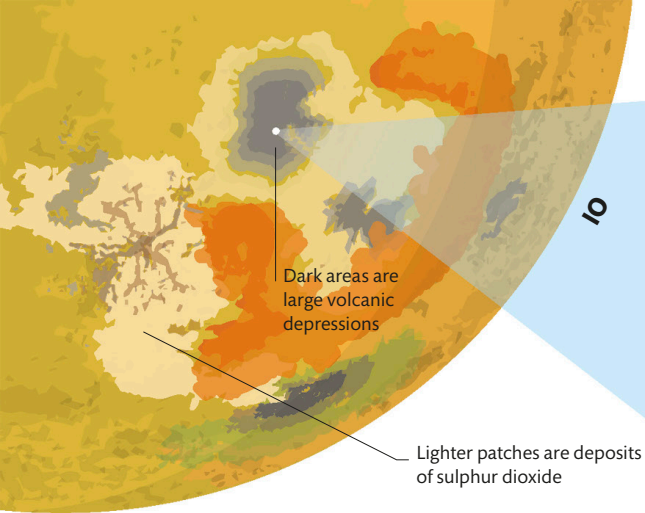


LIGHTNING IN JUPITER'S ATMOSPHERE STRIKES UP TO FOUR TIMES PER SECOND

JUPITER'S LIGHTNING

Lightning was first spotted on Jupiter in 1979 by the Voyager 1 spacecraft. These flashes, which typically appear near Jupiter's poles, are more powerful than lightning on Earth. Water vapour rises through Jupiter's interior and forms droplets in the atmosphere. Higher up, where it is colder, the droplets freeze. Electric charge builds up as the droplets collide in the cloud layers, then discharges as lightning.

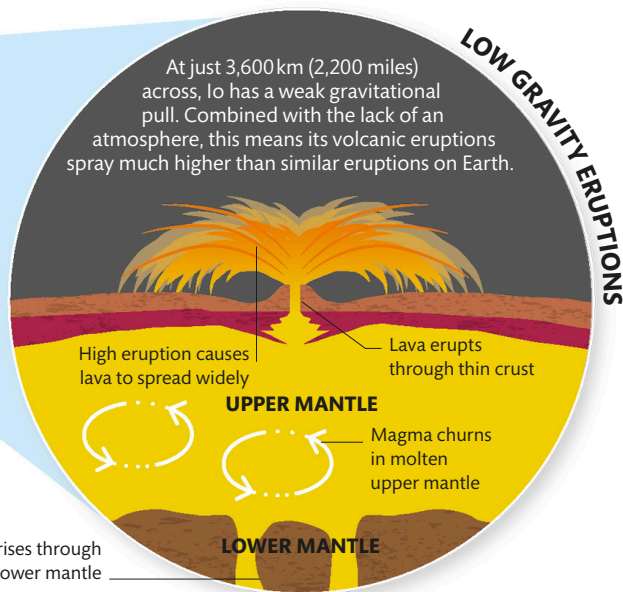




Io's surface

The surface of Io is constantly changing as volcanic plumes spew up subsurface material, creating lava lakes, mountains, and volcanoes that can stretch up to 250 km (155 miles) across.

Magma rises through solid lower mantle

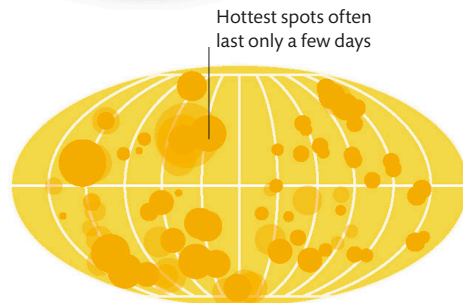


Io and Europa

Jupiter has 79 moons, two of which are among the most exciting, yet contrasting, moons in the Solar System. Both Io and Europa are shaped by Jupiter's immense gravitational pull.

Galilean satellites

Io and Europa are two of Jupiter's four largest moons, called the Galilean satellites. At a distance of only 420,000 km (260,000 miles) from Jupiter, Io's close orbit takes just 1.5 days to complete. As it does so, Io experiences huge tides that turn it into the most volcanically active place in the Solar System. Meanwhile, Europa is further away, taking 3.5 days to orbit Jupiter. It has less tidal heating but enough to make an ocean of water under the hard, icy crust.



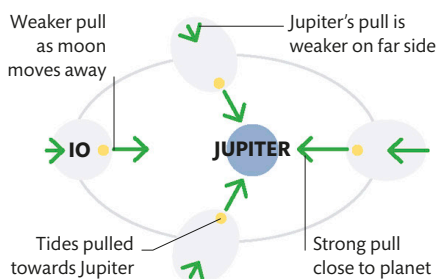
ERUPTIONS ON IO

Volcanic map

When mapped, Io's volcanic hot spots appear to be located at random, but they are more widely spaced at the moon's equator. Tectonic activity may be driving these areas apart.

TIDAL HEATING

Since Io travels on an elliptical orbit, its distance from Jupiter varies. As a result, the tidal forces due to Jupiter's gravity change too, constantly stretching and squeezing Io. This input of energy heats up the interior. Tidal heating affects all the Galilean satellites.



HOW MUCH DOES JUPITER STRETCH IO?

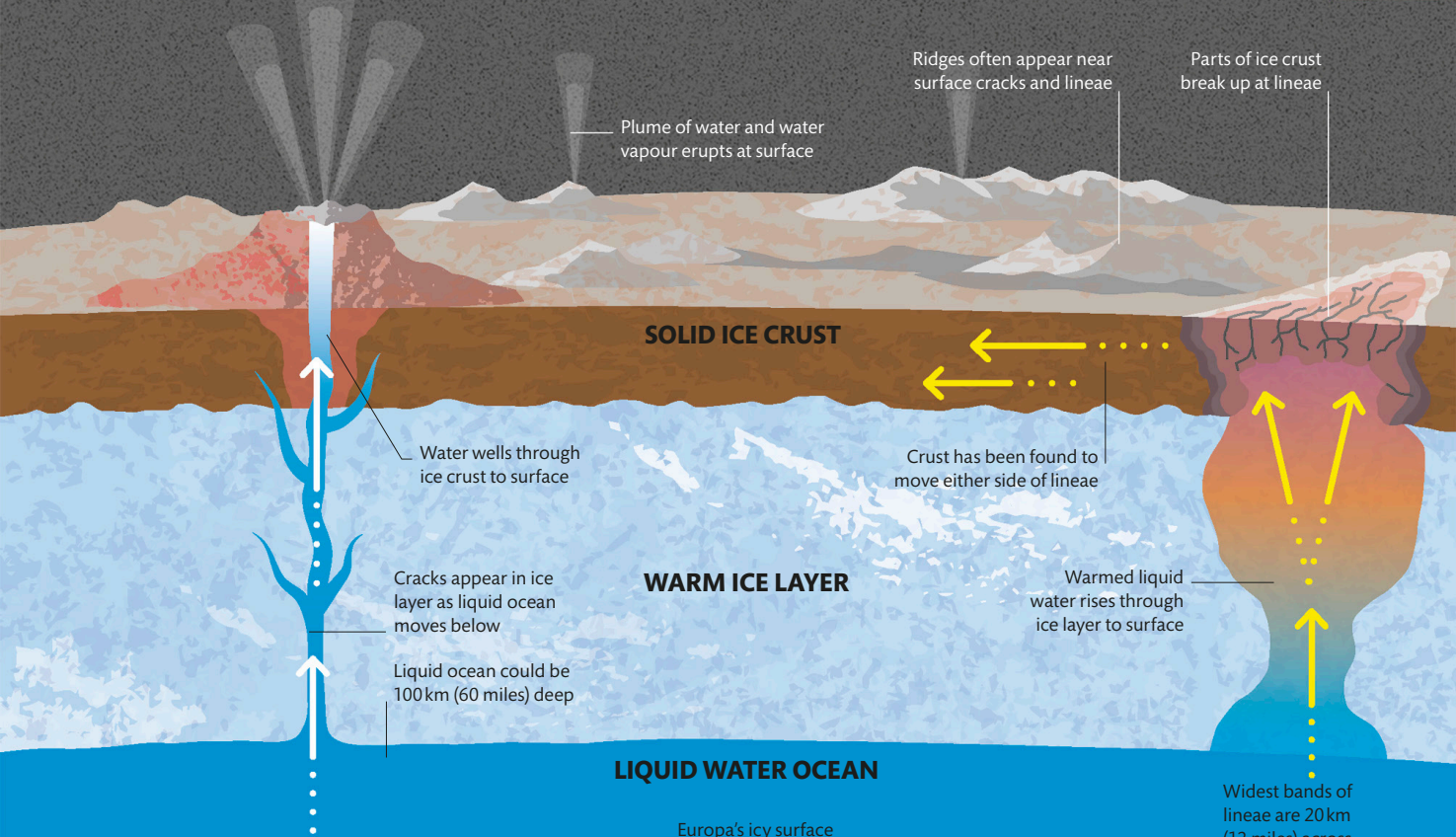
Jupiter's gravity and Io's elliptical orbit both cause the moon's surface to bulge. Its solid surface stretches by up to 100 m (330 ft) every 1.5 days.



Activity on Europa

Eruptions of liquid water and water vapour have been seen on Europa's surface. It is thought that water in the subsurface ocean, heated by tidal forces due to Jupiter, rises to the crust and bursts through the surface.

EUROPA HAS THE SMOOTHEST SURFACE OF ANY SOLID SOLAR SYSTEM BODY



Europa

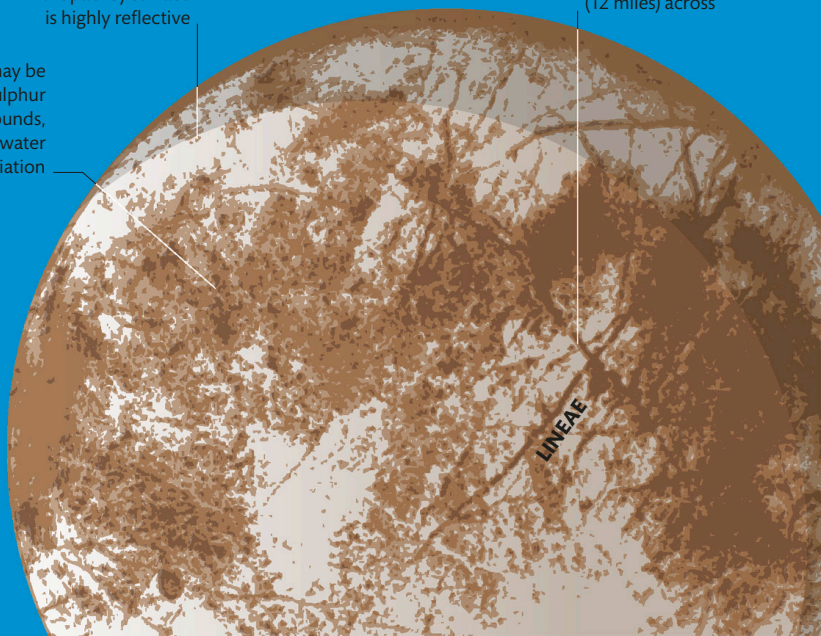
Europa's solid ice crust is streaked with lines, and there is much debate about how thick the ice is. Beneath the ice is an ocean that contains more liquid water than all of Earth's oceans, seas, lakes, and rivers combined, leading some scientists to believe it is a potential site to explore for signs of life. Under the ocean is a layer of rock on top of a metallic core.

Europa's surface

Dark streaks on Europa's surface, called lineae, are thought to be caused by the movement of water underneath. Similar features are seen close to Earth's ice caps.

Europa's icy surface is highly reflective
Dark spots may be salts and sulphur compounds, affected by water ice and radiation

EUROPA

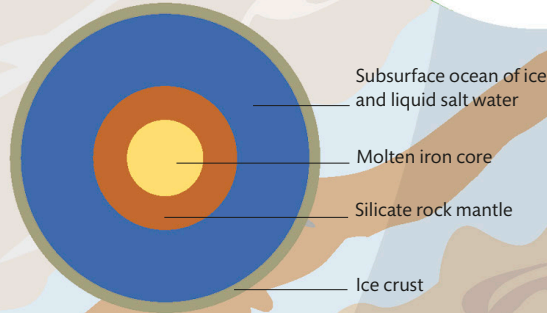


Ganymede and Callisto

The outer two Galilean satellites, Ganymede and Callisto, are larger and less active than Europa and Io. They are also scarred from billions of years' worth of high-energy impacts.

Ganymede

At 5,300 km (3,300 miles) wide, Ganymede is the biggest moon in the Solar System and larger than Mercury (although Ganymede is not as heavy). It has a thin atmosphere largely composed of oxygen and is also the only satellite known to have its own magnetic field, indicating that it has an iron core and distinct internal layers. Ganymede orbits Jupiter in a week and always shows the same side to its host. The moon's surface alternates between dark, cratered regions and light patches with ridges that may stem from tectonic activity.



Inside Ganymede

Ganymede has a liquid iron core with a temperature in excess of 1,500°C (2,700°F). This warms a layer of silicate rock and a vast subsurface ocean containing more water than on Earth. The surface is formed of a hard ice shell.

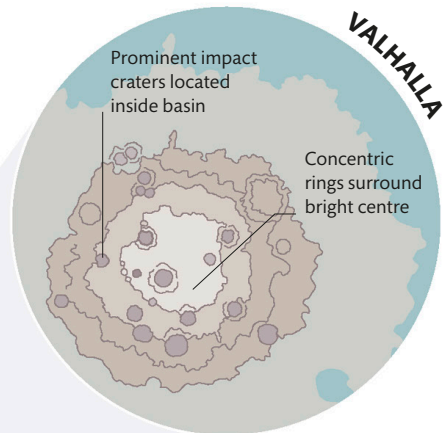
IF GANYMEDE IS SO BIG, WHY ISN'T IT A PLANET?

Although Ganymede is round and bigger than Mercury, it is not classified as a planet. All planets must orbit the Sun, but Ganymede orbits Jupiter.

JUPITER

Callisto

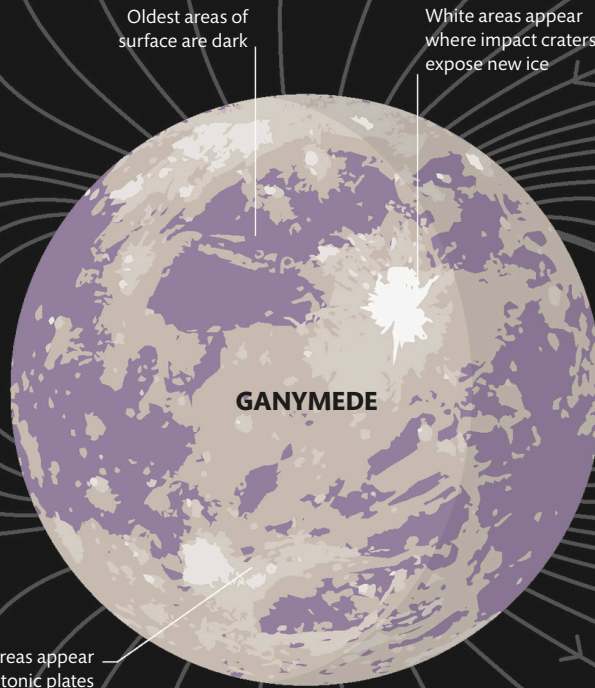
Callisto – only a little smaller than Mercury – is home to the Solar System's most heavily cratered surface. The impacts are very old and distinct, suggesting the moon's surface has not been altered by volcanic or tectonic activity for over four billion years. Callisto is also the only Galilean satellite not to undergo significant tidal heating. At almost 1.9 million km (1.2 million miles) from Jupiter, Callisto is the most distant major moon and is also less affected by Jupiter's powerful magnetosphere.



Multi-ring impact crater

Callisto has the largest multi-ring impact basin in the Solar System, called Valhalla. It stretches 3,800 km (2,400 miles) across.

CALLISTO IS THE MOST HEAVILY CRATERED OBJECT IN THE SOLAR SYSTEM



Oldest areas of surface are dark

White areas appear where impact craters expose new ice

GANYMEDE

Light areas appear where tectonic plates have pulled apart

Jupiter's magnetic field interacts with Ganymede's

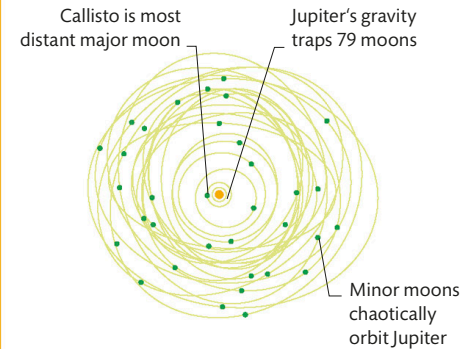
Ganymede's magnetosphere stretches over 10,000 km (6,000 miles) across

Magnetosphere

Ganymede's magnetic field – which is reversed compared to Jupiter's – forms a bubble inside Jupiter's own magnetosphere. Particles from Jupiter enter at the poles, creating auroral activity on Ganymede.

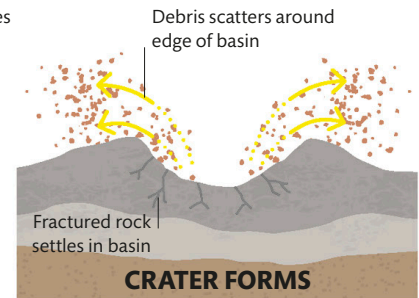
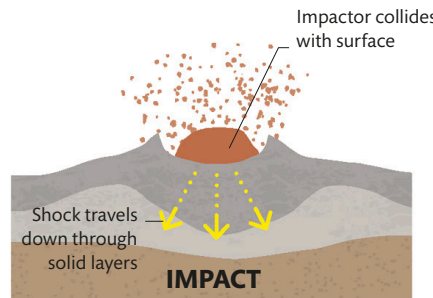
JUPITER'S OUTER MOONS

Unlike the Galilean satellites, the majority of Jupiter's moons are tiny objects captured by its immense gravity. Their orbits are randomly distributed, with many orbiting in the opposite direction to Jupiter's spin.



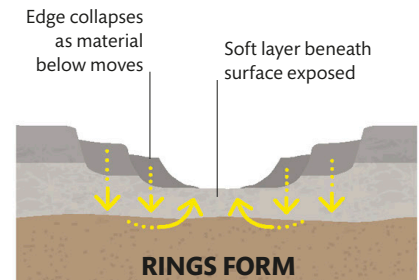
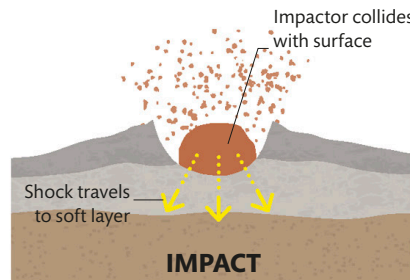
Typical crater formation

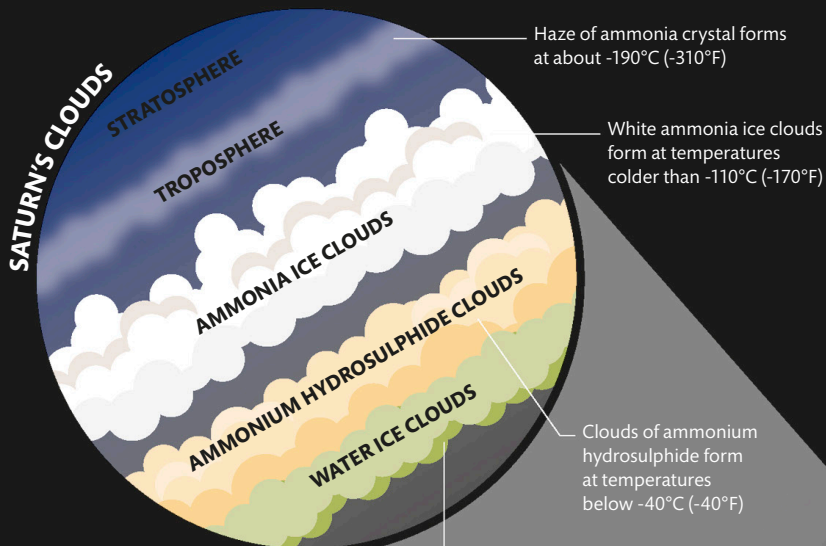
Many craters seen across the Solar System are created by large impacts, the force of which melts both the impactor and the impact site. After the initial shock effect, molten material rises and solidifies in the middle of the crater, and debris is often ejected and scattered around the edge of the crater. Chains of small craters are the result of impacts from comets torn into pieces by the moon's tidal forces.



Valhalla formation

This distinctive structure of concentric rings formed when an impact completely punctured the outer shell of Callisto's surface, exposing softer material below that may have been an ocean. This deeper material flowed towards the centre of the crater, filling up the space carved out by the impact. As the softer material moved, surface material around the edge of the crater collapsed, forming the rings.





Cloud layers

The atmosphere is formed of hydrogen, helium, and traces of ammonia, methane, and water vapour. Cold temperatures create layers of ice clouds as the gases freeze.

HOW FAR IS SATURN FROM THE SUN?

Saturn orbits at an average distance of 1.4 billion km (890 million miles) from the Sun. It takes 80 minutes for sunlight to reach Saturn, 10 times longer than for Earth.

Saturn

Saturn is the sixth planet from the Sun and the second largest planet in the Solar System. It is best known for its famous ring system.

The ringed planet

Saturn is a gas giant, formed of mostly hydrogen and helium, meaning that – unlike Earth or any of the other rocky planets – it has no real surface. With a radius of 58,000 km (36,000 miles), Saturn is nine times wider than Earth. While it is renowned for its rings, made almost entirely of ice, Saturn is not the only planet with rings. In fact, all four giant planets have them, but only Saturn's are clearly visible.

Inside Saturn

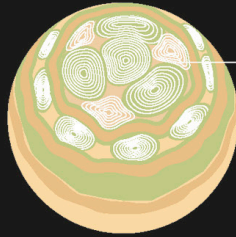
Scientists think that deep inside Saturn, under kilometres of gaseous atmosphere, is a layer of liquid molecular hydrogen. Below this, the hydrogen is under such pressure that the molecules break down into atoms and turn into a conductive liquid called metallic hydrogen. At the centre of the planet is a dense core, with a temperature up to $10,000^{\circ}\text{C}$ ($18,000^{\circ}\text{F}$), which might be solid or liquid.

Winds whip around atmosphere, pushing clouds into bands



Hexagonal vortex

Near Saturn's north pole is a hexagonal cloud pattern, or vortex, with each side around 14,500 km (9,000 miles) long. It is thought to be caused by complex turbulence in the atmosphere.



**NORTH POLE
TURBULENCE**

Swirling clouds
of vortex

Ring system extends up to
282,000 km (175,000 miles)
from planet

Saturn's rings might be icy
fragments from a moon that was
destroyed in a collision



**SATURN'S DENSITY IS SO
LOW THAT THE PLANET
WOULD FLOAT IN WATER**

Troposphere layer of
atmosphere is Saturn's
visible surface

Iapetus

Hyperion

Rhea

Helene

Calypso

Dione

Telesto

Tethys

Pandora

Enceladus has an
internal water ocean

Janus

Mimas

Epimetheus

Prometheus

Atlas

Pan

Saturn's moons

More than 60 moons orbit Saturn.
Some of the small inner moons
orbiting within the ring system
have the effect of creating gaps
and changing the ring structure.

Dense, hot core
may contain rock
and metal

ROCKY CORE

METALLIC HYDROGEN

MOLECULAR HYDROGEN

Liquid starts
becoming metallic

Liquid metallic
layer is source
of Saturn's
magnetic field

Liquid layer
consisting of
hydrogen and
helium under
pressure

Internal layers

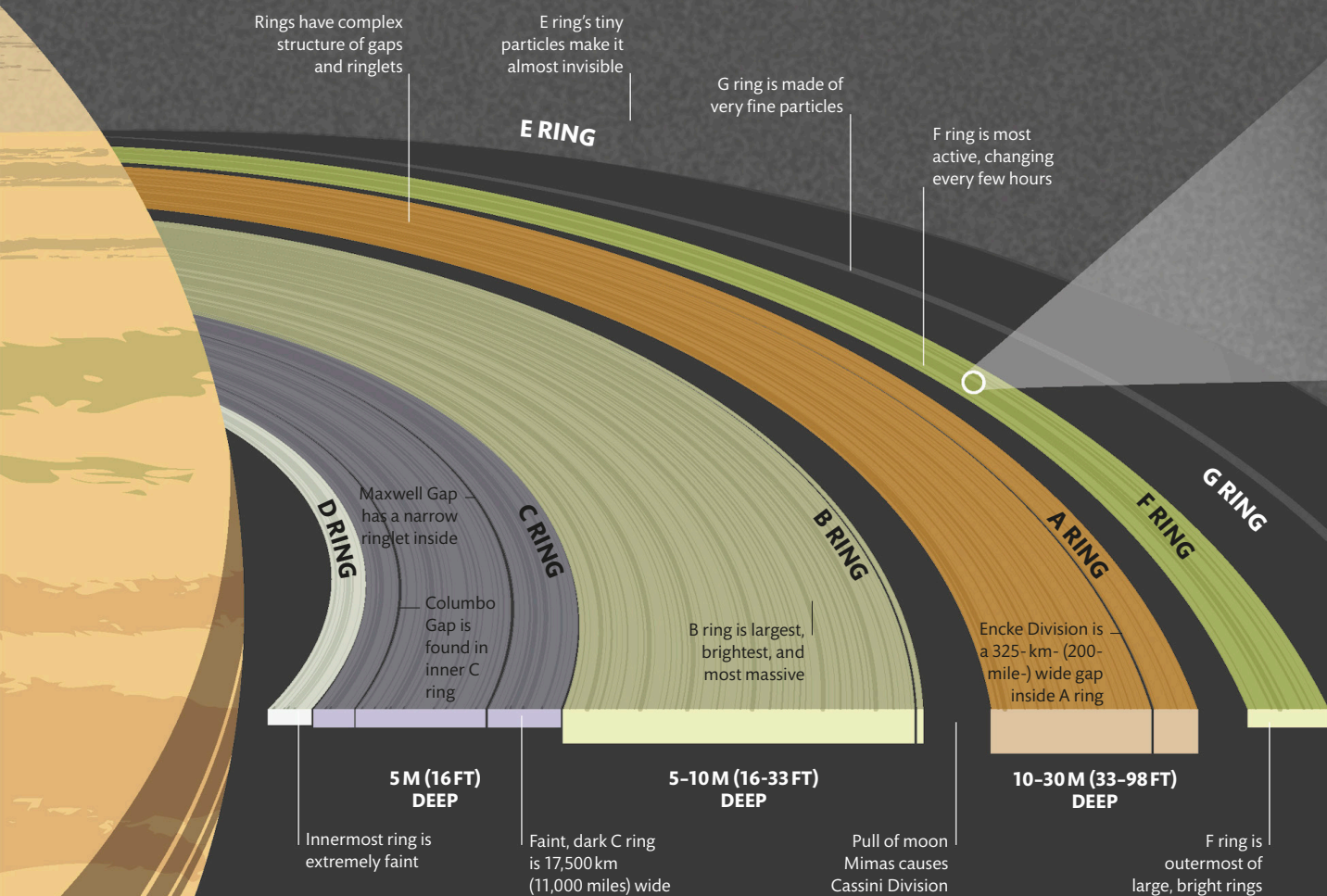
Saturn's internal layers are formed
of around 75 per cent hydrogen
and 25 per cent helium. The
layers change gradually as
pressure builds closer
to the core.

The inner rings

Saturn's rings are identified by letters that were allocated in the order in which they were discovered. The two brightest are the A and B rings, separated by the Cassini Division. Extending inwards from the B ring are the paler C and D rings, which contain smaller ice particles.

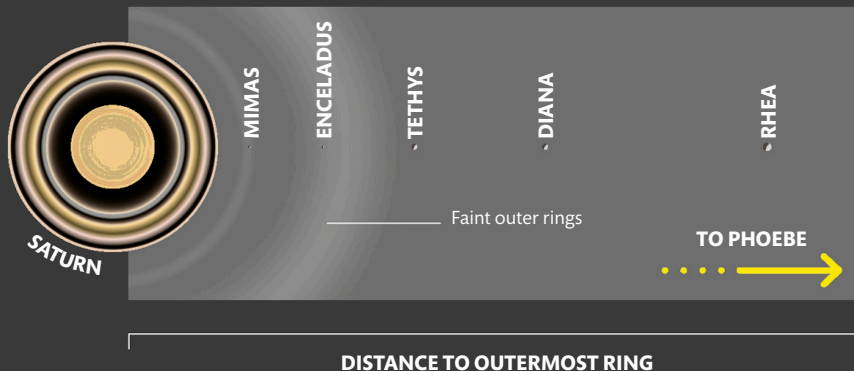


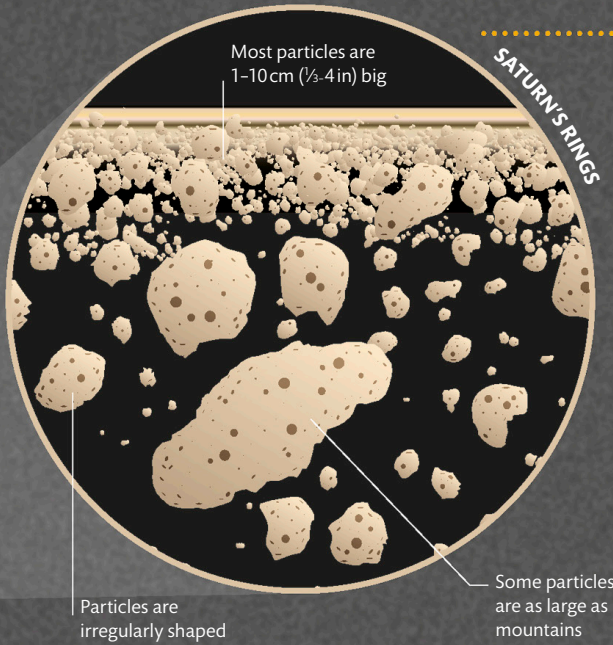
SATURN'S RINGS MIGHT HAVE FORMED ONLY 10-100 MILLION YEARS AGO - AFTER LIFE BEGAN ON EARTH



The outer rings

Beyond the distinct D to G rings is a series of extremely wide, faint outer rings that stretch out to the orbit of Saturn's moon Phoebe. The E ring is faintly visible, but the outermost ring, called the Phoebe ring because it stretches out to the moon Phoebe, is made up of particles so small the ring is almost invisible.





Ring materials

Saturn's rings are almost entirely made up of water ice, with some bits of dust and rock from passing comets, asteroids, and the impacts of meteorites on Saturn's moons. The chunks of ice in the rings range in size from dust particles to kilometres wide. The densest areas are inside the A and B rings, which were the first to be discovered as the high density of chunks they contain makes them more visible.

Ice particles

Inside, the particles are over 99.9 per cent water ice, with trace components of rocky materials. These materials include silicates and tholins, which are organic compounds created by cosmic rays interacting with hydrocarbons like methane.

WHAT COLOUR ARE THE RINGS?

Saturn's rings look whitish because they are almost entirely water ice. However, NASA's Cassini spacecraft distinguished pale shades of pink, grey, and brown, due to impurities.

Saturn's rings

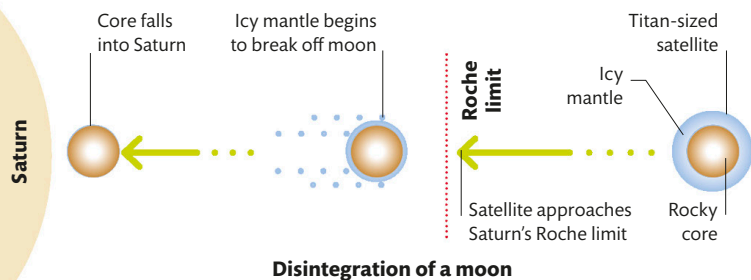
While the bright ring system around Saturn may look solid, the rings are in fact made of countless chunks of almost pure water ice, orbiting the gas giant in a series of distinct rings.

The ring system

Icy chunks forming the iconic rings of Saturn may be debris from a moon that broke up, or may even be left over from the giant planet's formation. Over time, these chunks were covered in layers of dust and started to orbit the planet. Saturn's rings have a typical thickness of 10–20m (33–66ft), but can reach a thickness of up to 1km (0.6 miles). The inner rings stretch out 175,000km (109,000 miles) from Saturn and are separated by gaps, caused by the gravitational pull of Saturn's moons. The largest gap, the Cassini Division, is 4,700km (2,900 miles) wide.

HOW THE RINGS FORMED

Exactly how Saturn's rings formed remains an uncertainty. A popular idea is that one of Saturn's moons moved in towards Saturn and broke up when it crossed the Roche limit, the point where the planet's tidal forces could tear it apart. In one theory, the ring pieces broke off the icy mantle of a large moon and then the rocky core of the moon spiralled into Saturn.



Inside Titan

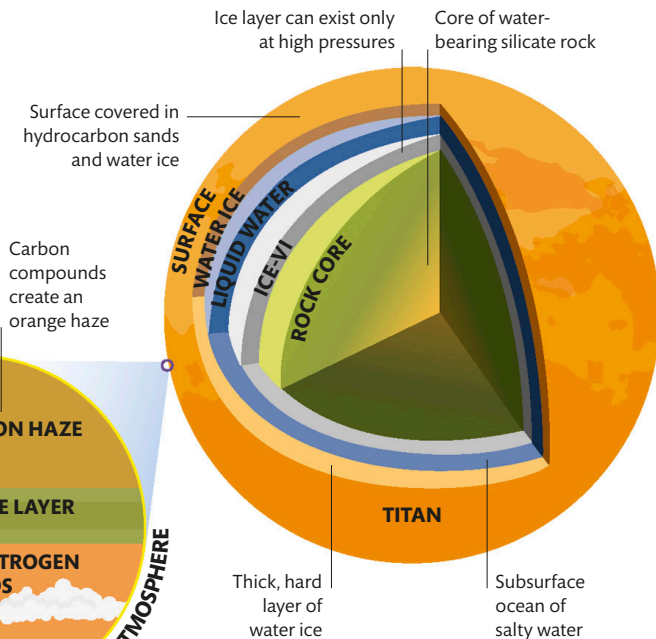
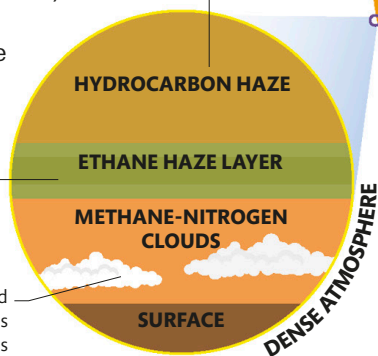
Information gathered by NASA's Cassini spacecraft indicates Titan's internal structure is made up of five layers. In the centre is a core of silicate rock around 4,000km (2,500 miles) in diameter. This is surrounded by a shell of ice-VI, a type of water ice that forms under high pressures. Above this is a layer of salty liquid water, followed by a layer of water ice. The outermost layer, Titan's surface, is made up of hydrocarbons (organic compounds of hydrogen and carbon) that have accumulated in the form of sands or liquids. A dense, high-pressure atmosphere extends 600km (370 miles) above the surface, into space.

Atmospheric elements

Titan's atmosphere is composed of around 95 per cent nitrogen and 5 per cent methane, with small amounts of organic compounds rich in hydrogen and carbon.

Ethane haze formed by solar radiation

Methane and nitrogen molecules form low clouds

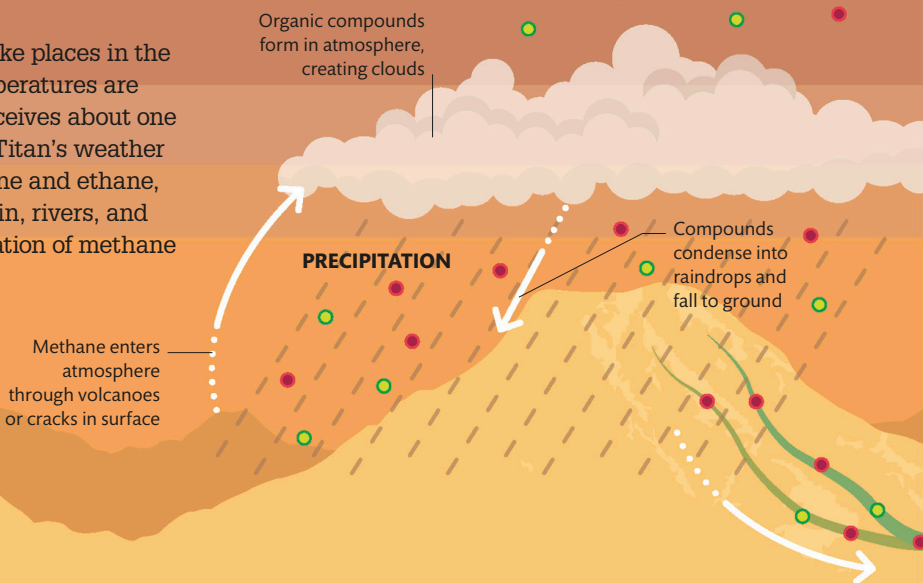


Titan's weather

Titan's surface is one of the most Earthlike places in the Solar System, but it is much colder. Temperatures are around -180°C (-290°F) as the surface receives about one per cent of the light that reaches Earth. Titan's weather cycle sees hydrocarbons, such as methane and ethane, cooled to the point of liquidity to form rain, rivers, and seas. The cycle starts with the accumulation of methane and nitrogen in the thick atmosphere.

HOW MUCH BIGGER IS TITAN THAN EARTH'S MOON?

Titan's diameter is 50 per cent larger than Earth's Moon, at 5,150 km (3,200 miles). Titan is also 80 per cent heavier thanks to its dense silicate core.



1

Organic compounds form

Methane from below the surface leaks out to the atmosphere. At high altitude, methane and nitrogen molecules are split apart by ultraviolet light from the Sun. The atoms then recombine to form organic compounds containing hydrogen and carbon.

2

Rain brings down compounds

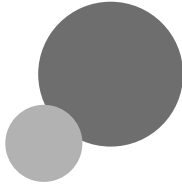
Some of the organic compounds accumulate in clouds and then fall to the ground as rain. The low gravity and dense atmosphere of Titan causes rain to fall at about 6 kph (4 mph), about six times slower than on Earth.



Titan

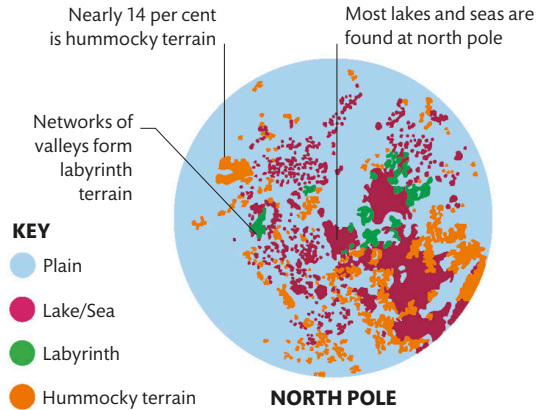
Saturn's biggest moon, and the second largest moon in the Solar System after Ganymede, Titan has clouds and rain and is covered in lakes. Titan is the only body in the Solar System with a cycle similar to Earth's water cycle. However, in Titan's case, it rains methane.

TITAN IS 5,150 KM (3,200 MILES) WIDE, BIGGER THAN THE PLANET MERCURY



IDENTIFYING TITAN'S LAKES

NASA's Cassini spacecraft used radar to map surface features and bodies of liquid methane and ethane on Titan. The way infrared radiation was absorbed or reflected also helped identify liquid.



ORGANIC COMPOUNDS FORM IN ATMOSPHERE

Heavier organic compounds fall directly to ground

DIRECT AIRFALL

3 Compounds flow to seas

Cold conditions on the surface cause the organic compounds to flow as liquids. Just like water on Earth, after being rained down they flow through rivers, making their way to the seas.

4 Matter settles as sludge

Some of the molecules produced in the atmosphere, like nitriles and benzene, are not soluble in methane. When they reach the seas, they sink to the sea floor and create a layer of organic-rich sludge.

Rain flows into streams, rivers, lakes, and seas

In seas, some compounds dissolve

LIQUID SEA

TRANSPORT BY RIVERS

KEY

Soluble compounds Insoluble compounds

Insoluble compounds fall to bottom

SLUDGE LAYER

SATURN

Ice giants

There are two giant ice planets – Uranus and Neptune – located in the outer Solar System. These large planets are made mostly of water, ammonia, and methane.

Uranus

Uranus, the seventh planet from the Sun, orbits slowly at a distance of around 2.9 billion km (1.8 billion miles), but it rotates quickly, taking around 17 hours to complete one rotation around its axis. At 51,000 km (32,000 miles) across, Uranus is about four times the width of Earth. It has 27 moons and 13 barely visible rings. Unlike most other planets, Uranus rotates east to west, possibly the result of a collision with an Earth-sized object.

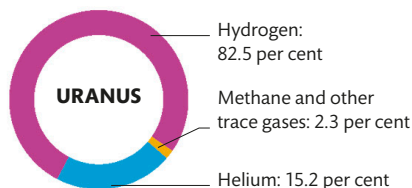
Inside Uranus

Beneath a deep atmosphere, Uranus gets most of its mass from a liquid mantle of water, ammonia, and methane – called “ices” because they are normally frozen in the outer Solar System. This surrounds a small rocky core. Although Uranus’s atmosphere is cold, its core may reach almost 5,000°C (9,000°F).

Upper atmosphere forms
Uranus’s visible surface

WHY ARE THE ICE GIANTS BLUE?

Methane in the atmospheres of both planets absorbs red sunlight so the reflected light looks blue. Neptune’s darker colour suggests there is another unknown chemical in its atmosphere.



Atmospheric composition

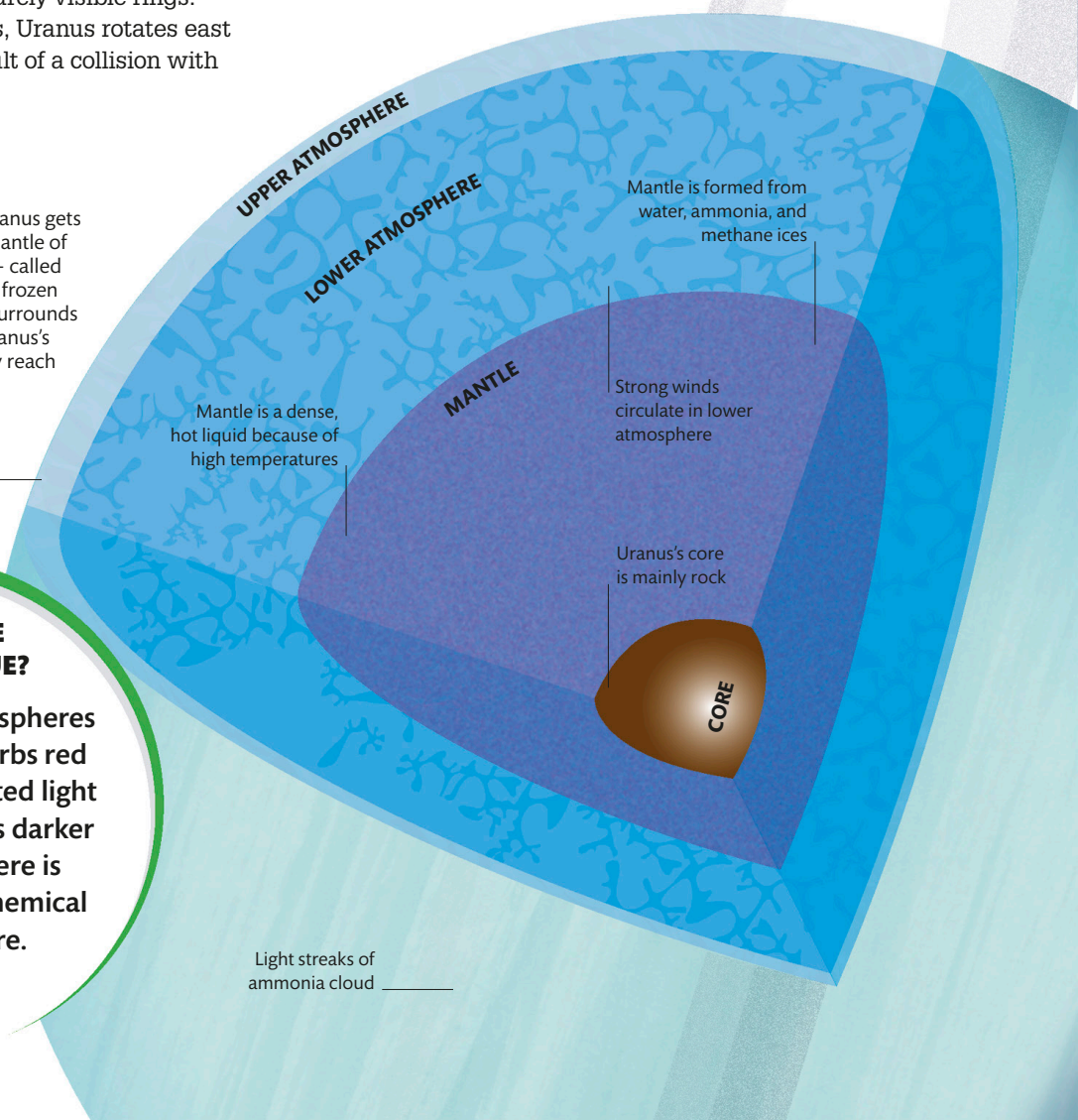
Uranus’s atmosphere is composed mostly of hydrogen and helium, with a small amount of methane and traces of water and ammonia. Neptune’s atmosphere has an almost identical composition.

Inner rings consist of nine narrow rings and two dusty rings

RINGS

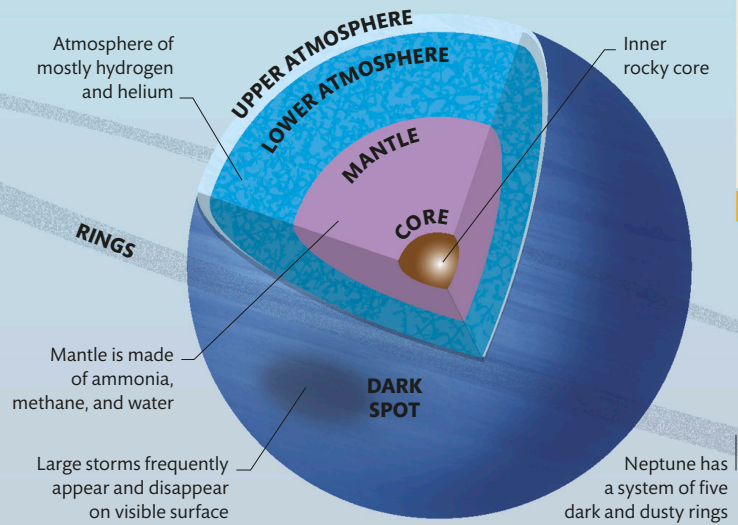
Two outer rings are broad and faint

Rings composed of dark particles made of ice and rock



Neptune

Neptune is the outermost planet in the Solar System, at a distance of about 4.5 billion km (2.8 billion miles) from the Sun. While it also appears blue, it is a darker shade than Uranus, and its clouds and a dark spot are signs of an active atmosphere. The movements of clouds on the visible surface have shown that Neptune has the strongest winds in the Solar System. Neptune is slightly smaller than Uranus, with 14 known moons and at least five rings.



Inside Neptune

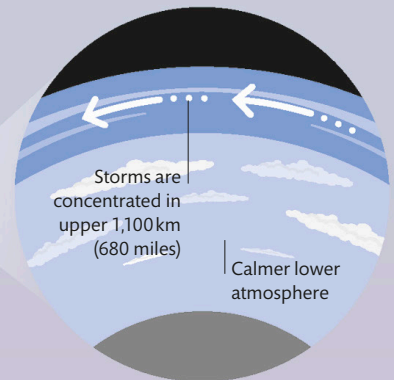
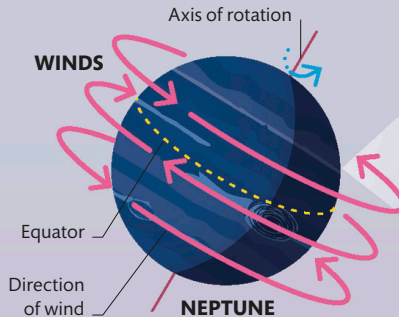
Like Uranus, Neptune's interior is made up of a core of rock and ice, followed by a mantle of water, ammonia, and methane ice. There might also be an ocean of super-hot water under Neptune's clouds.



PRESSURE INSIDE THE ICE GIANTS MAY FORM AN OCEAN OF DIAMONDS

Supersonic winds

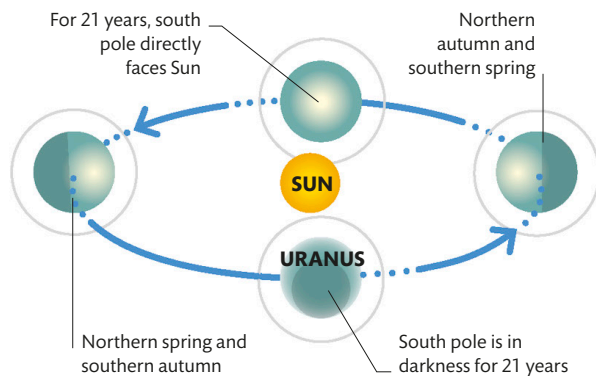
Neptune's strong winds whirl around the planet at speeds 1.5 times the speed of sound. Gravitational studies show these high-speed winds are contained in the upper atmosphere.



Sun's ultraviolet light interacting with atmosphere gives a hazy appearance

URANUS'S UNUSUAL SEASONS

Uranus's equator is nearly at a right angle to its orbital plane, with a tilt of almost 98° , possibly caused by a collision with a large object soon after the planet's formation. As a result, Uranus has the most extreme seasons of any planet in the Solar System. A quarter of Uranus's orbit, 21 years, is spent with one pole facing the Sun and the other in darkness.

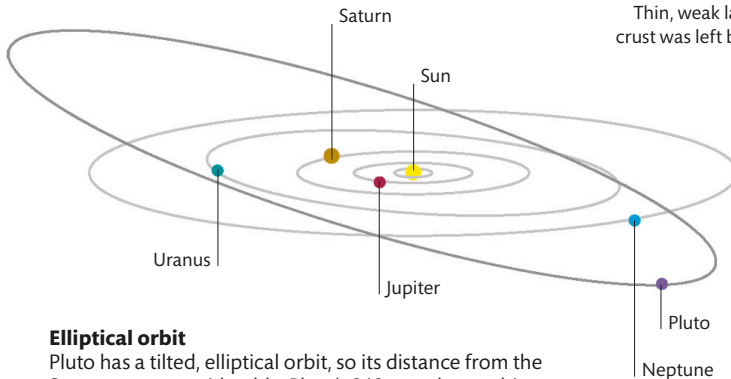


Pluto

Originally classified as a planet, Pluto was reclassified as a dwarf planet when similar worlds were discovered in the outer Solar System. This cold dwarf planet has a complex terrain with mountains and ice plains.

Surface features

Pluto is one of the larger dwarf planets, but it has a diameter of only 2,300 km (1,400 miles) – about two-thirds the size of Earth's moon. It orbits the Sun at an average distance of 5.9 billion km (3.7 billion miles), hence the cold surface temperatures. Pluto's surface is covered in mountains, valleys, and ice plains, the most distinctive of which is the ice plain Sputnik Planitia. Stretching 1,000 km (600 miles) across, this plain formed when a Kuiper Belt object collided with Pluto.

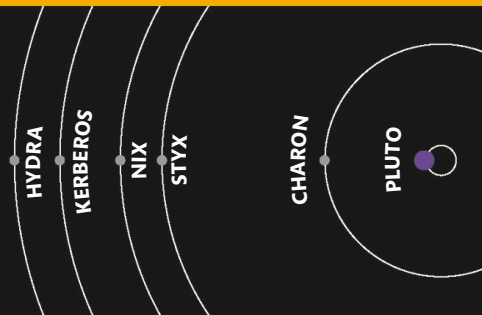


Elliptical orbit

Pluto has a tilted, elliptical orbit, so its distance from the Sun can vary considerably. Pluto's 248-year-long orbit takes it as far as 7.4 billion km (4.6 billion miles) from the Sun and as close as 4.4 billion km (2.7 billion miles).

PLUTO'S MOONS

Pluto is orbited by five moons, formed by a collision between Pluto and a similarly sized body. The largest moon, Charon, is around half Pluto's size and so similar that they are sometimes considered to be a double-planet system.



Kuiper Belt object 50–100 km (30–60 miles) across collided with Pluto

Large area of icy crust was removed

Thin, weak layer of crust was left behind

Ocean beneath surface pushed against weak layer, extending scarring

Sputnik Planitia

A large object colliding with Pluto and exposing the crust may have created its most prominent feature. Ice slush from a subsurface ocean and frozen nitrogen then formed plains, troughs, and hills.

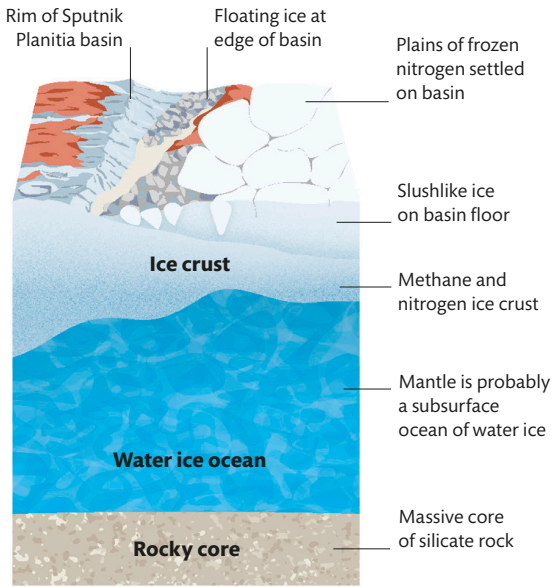


PLUTO'S ORBIT BRINGS IT CLOSER TO THE SUN THAN NEPTUNE



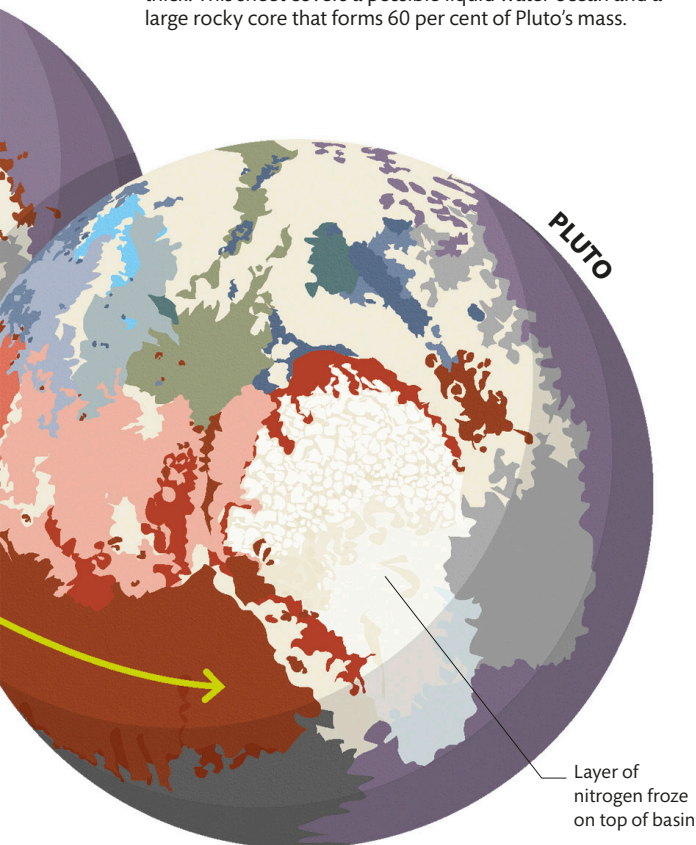
HOW OLD IS PLUTO?

Like most things in the Kuiper Belt, Pluto formed in the very early Solar System, about 4.5 billion years ago. The collision that formed Sputnik Planitia occurred 4 billion years ago.



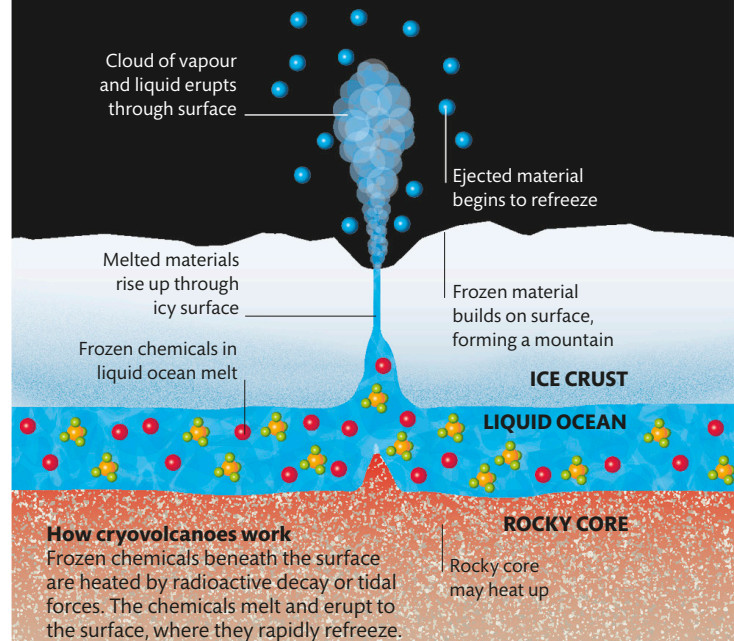
Internal structure

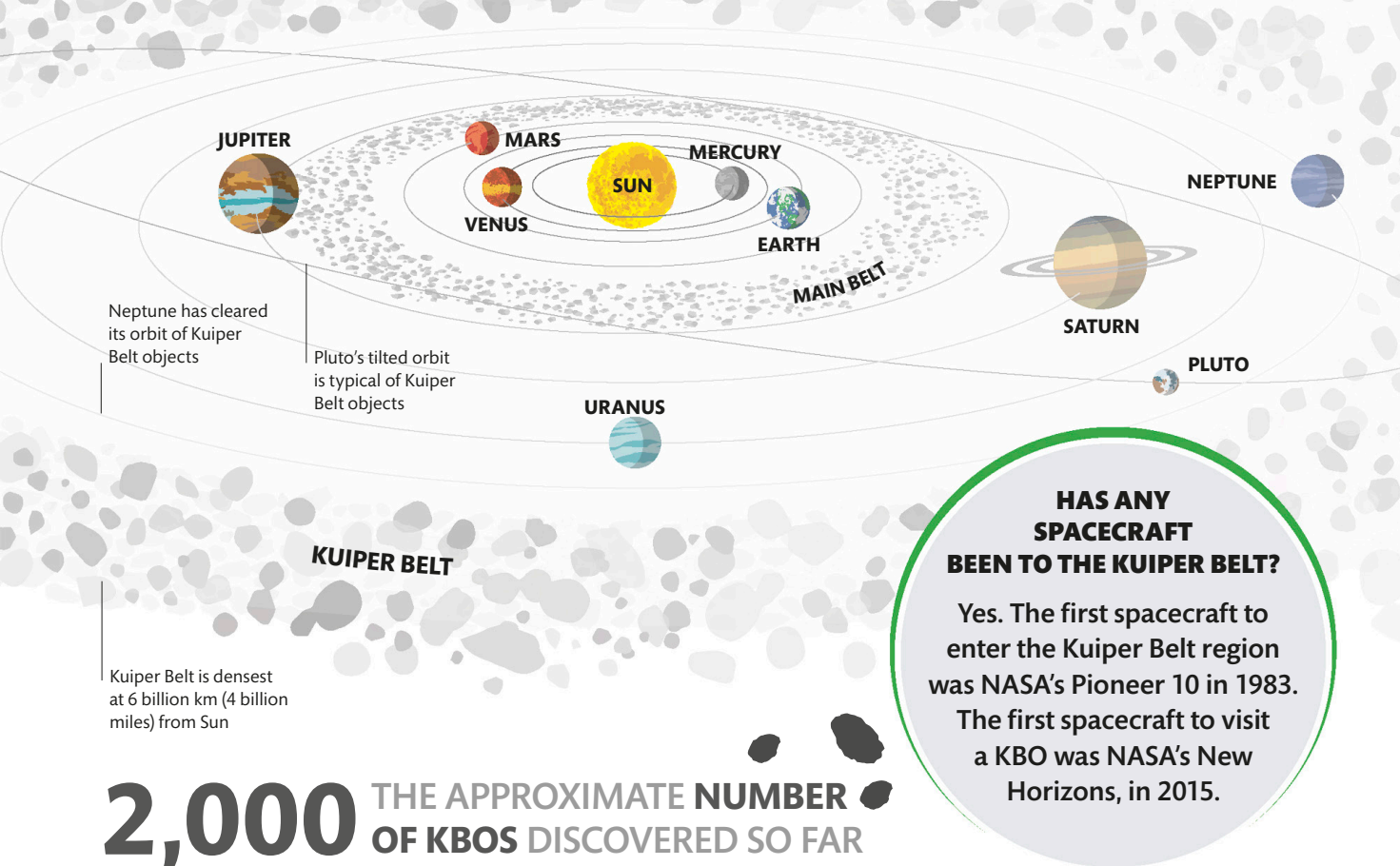
Pluto's crust is formed of an ice sheet at least 4 km (2.5 miles) thick. This sheet covers a possible liquid water ocean and a large rocky core that forms 60 per cent of Pluto's mass.



Pluto's volcanoes

To the south of Sputnik Planitia there are two huge, strange-looking mountains. The larger one, Piccard Mons, is 7 km (4 miles) high and 225 km (140 miles) wide. It is thought they may be cryovolcanoes. Instead of an eruption of molten rock, cryovolcanoes send liquids or vapours of chemicals such as water, ammonia, and methane into the atmosphere. They occur in places where the surrounding temperature is extremely cold.



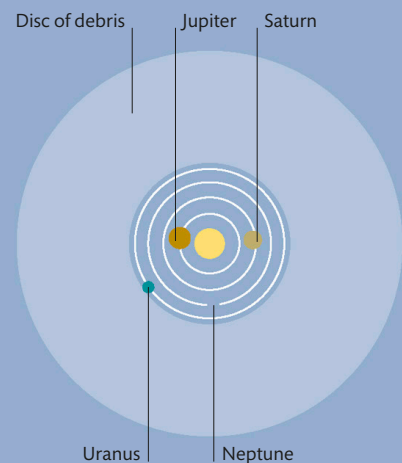


The Kuiper Belt

In the outer part of the Solar System, extending beyond the orbit of Neptune, is a doughnut-shaped ring of icy objects called the Kuiper Belt.

How the Kuiper Belt formed

The planets in the Solar System formed when gas, dust, and rocks pulled together under gravity. Beyond the planets, a disc of debris was left. Over time, the planets Saturn, Uranus, and Neptune migrated outwards. The giant planet Neptune, orbiting close to the disc of debris, disturbed the orbits of objects inside it. Neptune's gravity scattered many of them further from the Sun, into the Oort Cloud (pp.84–85) or out of the Solar System completely. In the end, only a small fraction of the original number of objects was left. Even so, many millions of small icy bodies are believed to remain in the Kuiper Belt region.



- 1 Compact ring of debris**
Objects in the Kuiper Belt, along with Neptune and Uranus, are thought to have formed closer to the Sun than they are now. The objects may have come from a disc of protoplanetary debris near to the planets.



Kuiper Belt objects (KBOs)

There are potentially millions of icy objects floating around in the Kuiper Belt. They are generally white, but their colour can change to red as a result of solar radiation.

Frozen Kuiper Belt objects have a temperature around -220°C (-360°F)

The icy belt

Extending from the orbit of Neptune, at about 4.5 billion km (2.8 billion miles) from the Sun, to 8 billion km (5 billion miles), the Kuiper Belt is similar to the Main Belt (see pp.60–61) but much bigger. Being so far from the Sun, it is a cold and dark place. It is home to hundreds of thousands of icy objects more than 100km (60 miles) across, made up mostly of frozen ammonia, water, and methane. Some have moons, and they include larger objects classed as dwarf planets. The Kuiper Belt is also the area where some comets originate (see pp.84–85).

DWARF PLANETS

Four of the largest objects beyond Neptune are classed as dwarf planets. Dwarf planets orbit the Sun and have become rounded under the force of their own gravity, but they are not large enough to clear other objects out of their orbit.



Pluto
At 2,400 km (1,500 miles) across, Pluto is the largest dwarf planet.



Eris
Eris is very slightly smaller than Pluto, but it is more massive.



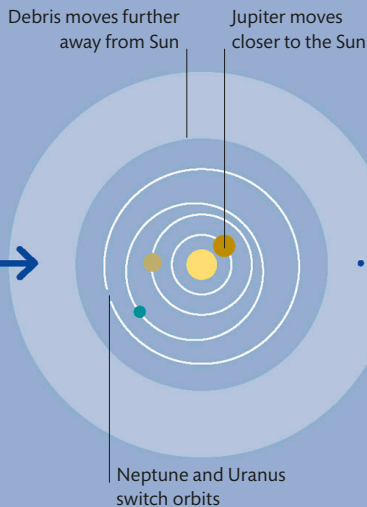
Makemake
Makemake is about two-thirds the size of Pluto and has a small moon.



Haumea
Egg-shaped Haumea has two moons and a ring system around it.



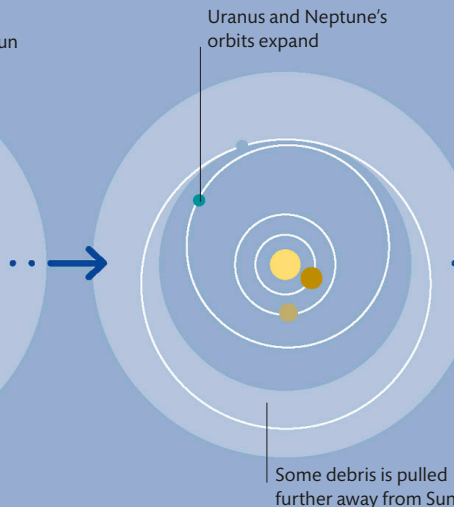
Ceres
Ceres, in the Main Belt, is the only dwarf planet not orbiting beyond Neptune.



2

Planet orbits change

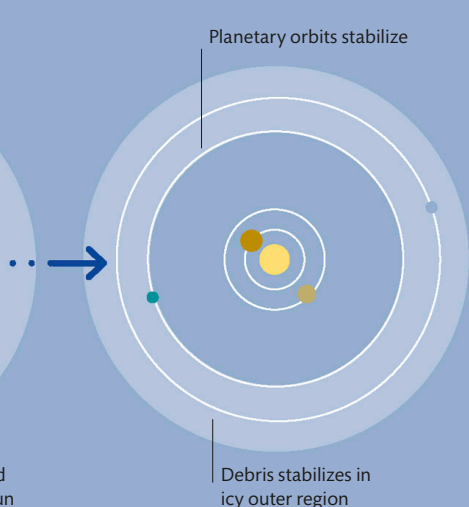
In a theory called the Nice model, Saturn, Uranus, and Neptune are thought to have drifted outwards, while Jupiter drifted closer towards the Sun. Uranus and Neptune also switched places with each other.



3

Planets interact with debris

As Uranus and Neptune drifted away from the Sun, they are thought to have carried with them some of their surrounding debris. This brought the debris into the colder outer region of the Solar System.



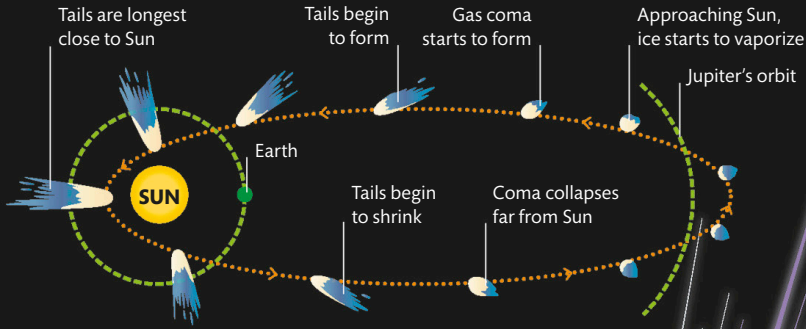
4

Kuiper Belt stabilizes

Over time, the orbits of the planets and icy objects became stable, creating the Kuiper Belt that exists today. However, some objects are occasionally still disturbed if their orbits bring them too close to Neptune.

Comets

Made up of dust and ice left over from the formation of the planets, comets originate as frozen bodies at the outer edge of the Solar System. In this state, they can be up to tens of kilometres across. When these objects are knocked out of a regular orbit, they are sent on orbits that bring them close to the Sun. When they approach the Sun, they transform into comets.

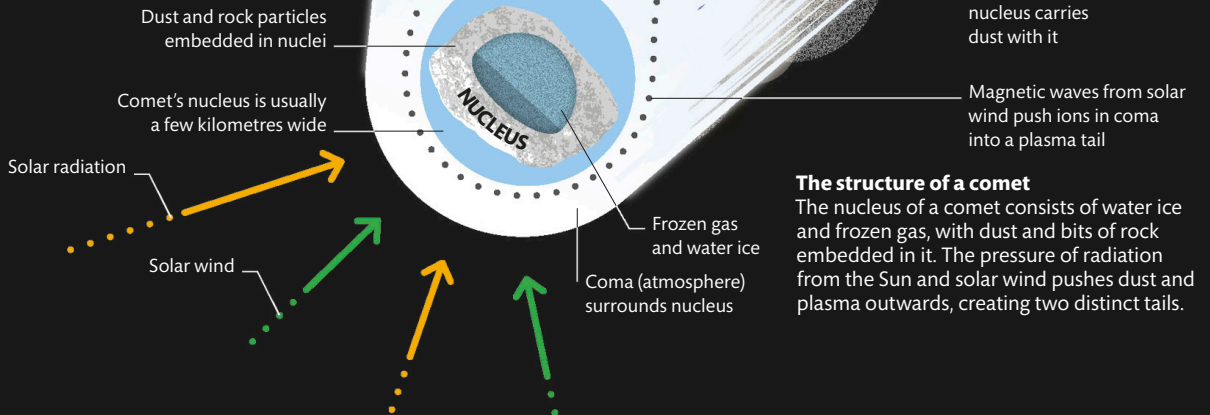


The life of a comet

When a comet approaches the Sun, ice on its surface vaporizes, creating an atmosphere called a coma and two tails. The coma collapses when the orbit carries the comet far enough away from the Sun and the tails fade.

IONIZED PARTICLES

High-speed particles in the solar wind interact with ionized particles, or plasmas, in the comet's coma. This creates a plasma tail, sometimes called a gas or ion tail.



The structure of a comet

The nucleus of a comet consists of water ice and frozen gas, with dust and bits of rock embedded in it. The pressure of radiation from the Sun and solar wind pushes dust and plasma outwards, creating two distinct tails.



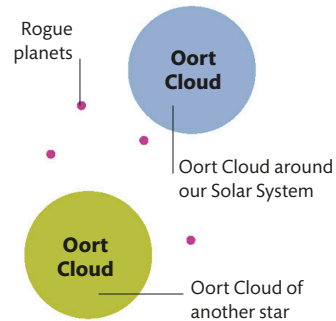
HOW LARGE IS A COMET'S COMA?

A coma – the atmosphere surrounding the nucleus of a comet – can be thousands of kilometres across. The comas of some comets are even larger than Earth.

Comet tails can stretch for hundreds of thousands of kilometres

ROGUE PLANETS

Beyond the Oort Cloud, it is possible that there are planet-sized objects, called rogue planets, which do not orbit any star. They might have formed from material that orbited a star and was then ejected, or these rogue planets simply may never have orbited a star.



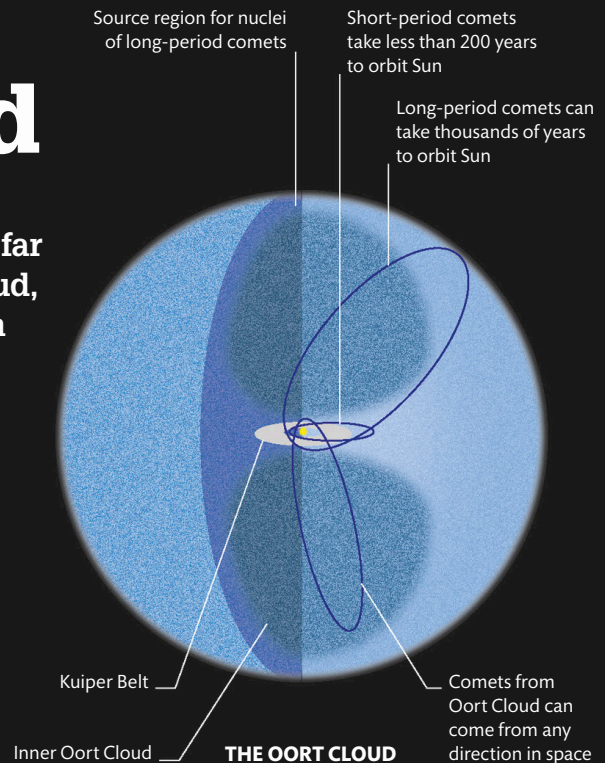
THE OORT CLOUD MIGHT CONTAIN BILLIONS, OR EVEN TRILLIONS, OF OBJECTS

Comets and the Oort Cloud

Astronomers think that the Solar System is surrounded by a swarm of icy bodies, lying far beyond the Kuiper Belt. Called the Oort Cloud, it is the source of long-period comets, which sometimes reach the inner Solar System.

The Oort Cloud

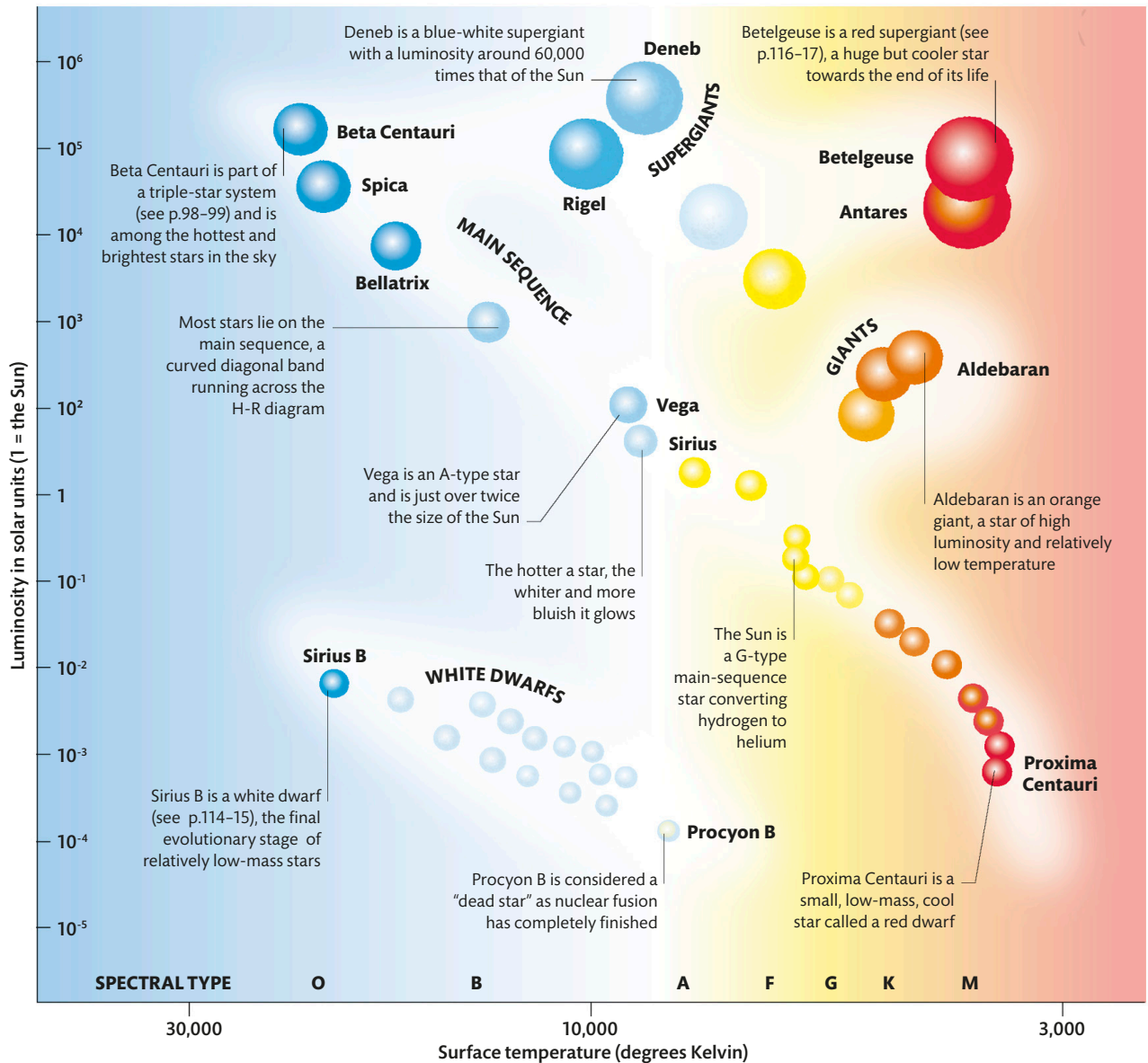
The Oort Cloud is thought to start around 300 billion–750 billion km (190 billion–470 billion miles) from the Sun, and end 1.5 trillion–15 trillion km (0.9 trillion–9 trillion miles) from the Sun. This means the outer edge could sit halfway between the Sun and its nearest star. In the Oort Cloud, objects orbit the Sun on paths tilted at all angles, unlike in the Main Belt (see pp.60–61) and the Kuiper Belt (see pp.82–83) where most follow orbits close to the main plane of the Solar System.





STARS

MAIN-SEQUENCE STAR TYPES					
Spectral type	Colour	Approximate surface temperature (Kelvin)	Average mass (The Sun = 1)	Average radius (The Sun = 1)	Average luminosity (The Sun = 1)
O	Blue	Over 25,000 K	Over 18	Over 7.4	20,000–1,000,000
B	Blue-white	11,000–25,000 K	3.2–18	2.5–7.4	11,000–20,000
A	White	7,500–11,000 K	1.7–3.2	1.3–2.5	6–80
F	Yellow to white	6,000–7,500 K	1.1–1.7	1.1–1.3	1.3–6
G	Yellow	5,000–6,000 K	0.78–1.10	0.85–1.05	0.40–1.26
K	Orange to red	3,500–5,000 K	0.60–0.78	0.51–0.85	0.07–0.40
M	Red	Under 3,500 K	0.10–0.60	0.13–0.51	0.0008–0.072





Classifying stars

Stars can be classified using the H-R diagram (see left). Those that convert hydrogen into helium through nuclear fusion (see p.90) are known as main-sequence stars. These stars, in the stable middle stages of their lives, are located within a diagonal band in the middle of the H-R diagram. Main-sequence stars are classified into seven groups – O, B, A, F, G, K, and M – according to their spectra, the patterns in the colours of light stars emit caused by the chemical elements they contain. These spectral types run from the hottest O-type down to the coolest M-type stars. Only stars near the ends of their lives, such as white dwarfs and supergiants, fall outside the band. These stars have exhausted their supply of hydrogen and become unstable.

The H-R diagram

This famous chart was named after astronomers Ejnar Hertzsprung and Henry Russell and illustrates the relationship between a star's temperature and luminosity. Stars remain on the curved diagonal main sequence for most of their lives. Low-mass stars are red and at the bottom right. Blue stars at the top left have the highest masses. Giants and supergiants, which have exhausted their hydrogen supply, lie at the top right.

WHAT IS THE BRIGHTEST STAR IN THE NIGHT SKY?

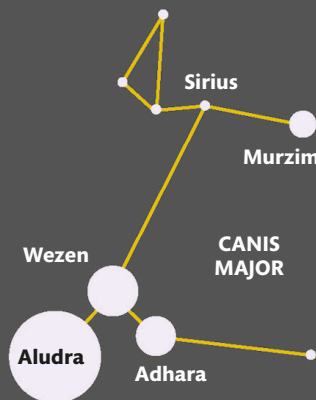
Sirius, also known as the Dog Star, in the constellation Canis Major, is the brightest star, with an apparent magnitude of -1.47.

Types of star

Stars are so far away from us that it is hard to tell how big, or even how bright, they really are. But astronomers can group them into categories by analysing their spectra (see pp.26–27), which differ according to a star's size and temperature.

Luminosity and brightness

Luminosity is the energy a star emits each second. The brightness of a star as it appears in our sky is called its apparent magnitude and depends on both the star's luminosity and its distance from Earth. It is measured on a numerical scale in which the brightest stars are given negative or low numbers (the brightest stars have values of around -1) and faint stars are given high numbers. The scale does not work in even-sized steps – a star with a magnitude of 1 is 100 times brighter than a star of magnitude 6.



Luminosity

The size of the white dots represents the true luminosity of stars in the constellation Canis Major. But the stars that radiate the most light may not look like the brightest stars in the night sky to us on Earth if they are far away.



Apparent magnitude

Here, the size shows the apparent brightness of the same Canis Major stars. Notice how Sirius looks much brighter because it is closer, but Aludra, 176,000 times brighter than the Sun, is quite dim because it is so distant.

THE MOST LUMINOUS STARS EMIT
BILLIONS OF TIMES MORE LIGHT
THAN THE FAINTEST STARS



Inside stars

Stars shine because they are heated to enormous temperatures by nuclear reactions. Deep inside, hydrogen nuclei are squeezed together so hard by the gravity of the star that they fuse to form helium nuclei, releasing energy.

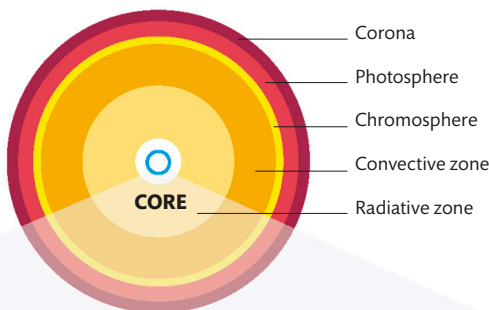
A star's energy source

Stars are powered through nuclear fusion, principally through the conversion of hydrogen to helium. We know that this takes place because there is no other way something as massive as a star could generate so much energy over its lifetime. The fusion process in stars releases tiny particles called neutrinos, and on Earth we can detect neutrinos emanating from the Sun. Studies of vibrations in the Sun also reveal its inner structure, just as earthquakes reveal what is inside the Earth.

ARE WE MADE OF STARDUST?

Nearly every element in the human body was made in stars over billions of years. The main exceptions are hydrogen and helium, which formed during the Big Bang.

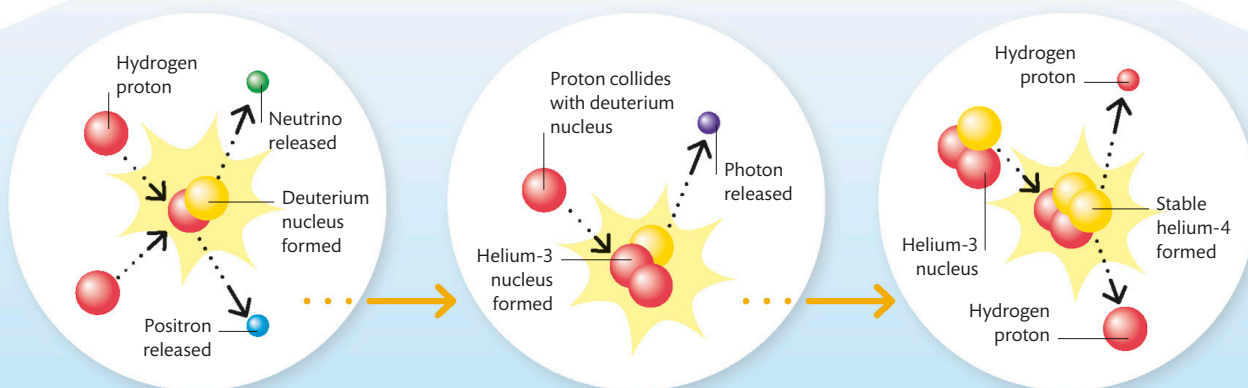
10 BILLION
THE NUMBER OF YEARS
IT WILL TAKE THE
SUN TO USE UP
ALL OF ITS
HYDROGEN FUEL



KEY

- Proton
- Positron
- Neutrino
- Neutron
- Photon

LAYERS OF A STAR SIMILAR TO THE SUN



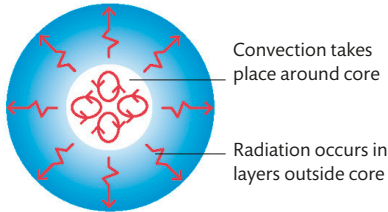
- 1 Protons combine**
Fusion begins when two hydrogen nuclei (protons) join together to form a deuterium nucleus. A positron and a neutrino are released as by-products.
- 2 Radiation released**
The deuterium nucleus is hit by another proton, which join to form a helium-3 nucleus. This releases a huge amount of energy in the form of heat and particles called photons.
- 3 Helium produced**
The helium-3 nucleus is bombarded by another, creating a helium-4 nucleus. When they join together, they emit two protons, which can start further fusions.



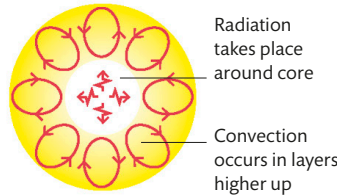
Heat transfer

The layers of stars move heat up and outwards mainly by convection and radiation. Convection occurs mostly when radiation is too slow at carrying heat away from the core. In low-mass stars, heat is transferred entirely by convection.

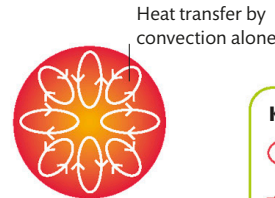
In stars of medium mass, such as the Sun, radiation dominates in the region surrounding the core, but convection takes over in the cooler outer layers, which absorb radiation. In high-mass stars, fusion generates energy so fast that convection dominates around the core.



OVER 1.5 TIMES THE MASS OF THE SUN



0.5-1.5 TIMES THE MASS OF THE SUN



UNDER 0.5 TIMES THE MASS OF THE SUN

KEY

-  Convection
-  Radiation

Making elements

Most of the lighter natural elements, except hydrogen and helium, were created either by gradual nuclear fusion in stars over their lifetime, or when stars suddenly exploded as supernovae. Elements heavier than iron cannot be made in a star's core because iron nuclei cannot be fused. Some of the heavier elements were made in the cores of dying red giants, which do not explode. The rest are believed to come from the violent explosion of two neutron stars merging.

Hydrogen, the first element to fuse, forms an envelope

Hydrogen converted into helium during process of nuclear fusion (see left)

Helium fuses to make carbon and oxygen in triple alpha process (see p.111)

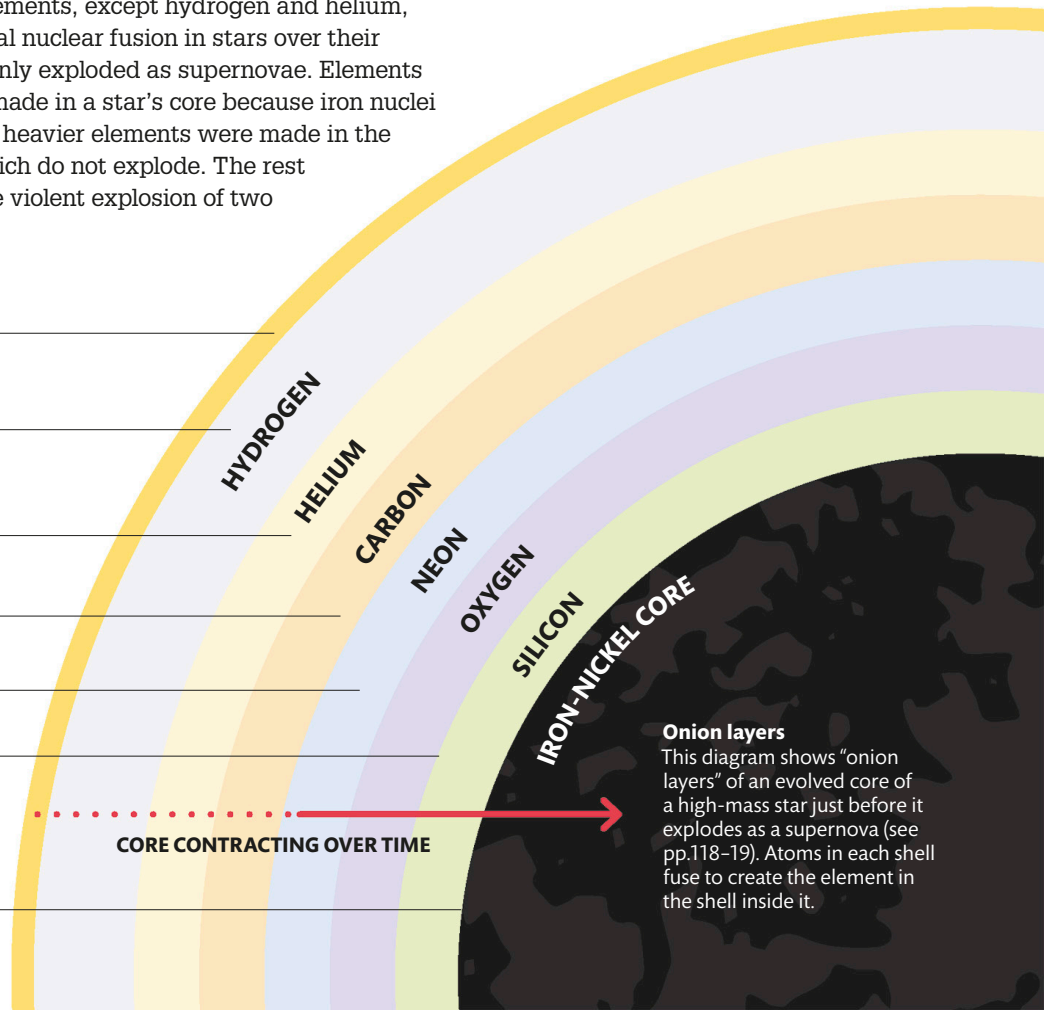
Carbon fuses to make sodium and neon

Neon fuses into oxygen, then magnesium

Oxygen fuses to make silicon

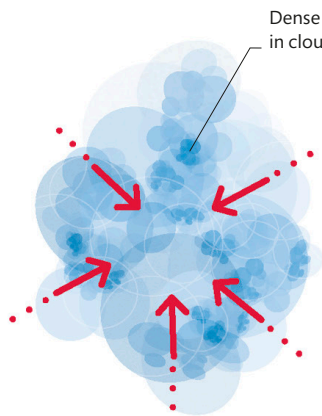
In supergiant stars, silicon fuses to make iron, signalling end of star's life

CORE CONTRACTING OVER TIME

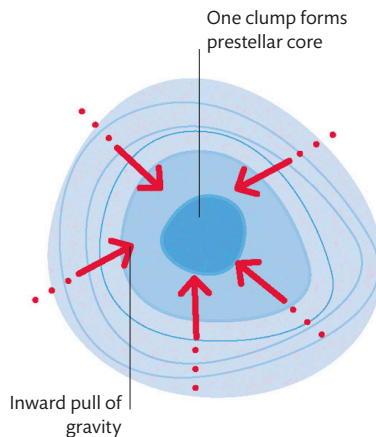


Onion layers

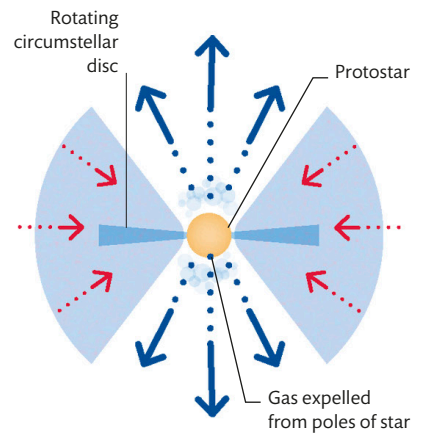
This diagram shows "onion layers" of an evolved core of a high-mass star just before it explodes as a supernova (see pp.118-19). Atoms in each shell fuse to create the element in the shell inside it.



- 1 Dense regions form**
The process begins when denser regions form in a space cloud. Molecules in these regions pull in together, creating clumps throughout the cloud. Each one of these clumps may eventually become a star.



- 2 Core collapses**
The core of each clump is denser than the outer parts so it collapses faster. As a result, it rotates ever faster, conserving angular momentum, like ice skaters pulling in their arms in as they spin.



- 3 Protostar formed**
The prestellar core forms a protostar and is surrounded by a rotating disc of gas and dust. The wider cloud flattens and starts to clear. Some gas is fired out in jets from the poles of the protostar.

Star formation

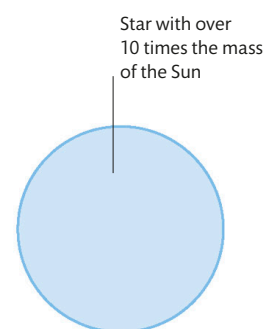
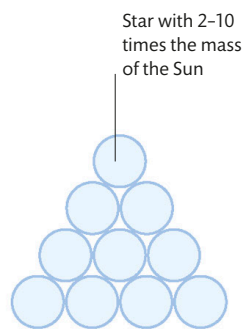
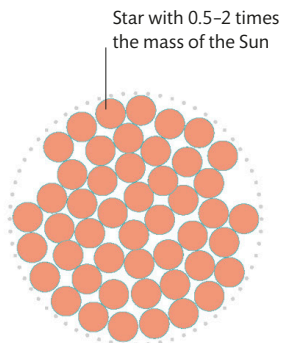
Stars are continually forming in galaxies all over the Universe. They are born as protostars in vast clouds of gas and dust called giant molecular clouds and go on to evolve into stable main-sequence stars. By studying many stars at different points in their lives, astronomers can determine the stages they undergo.

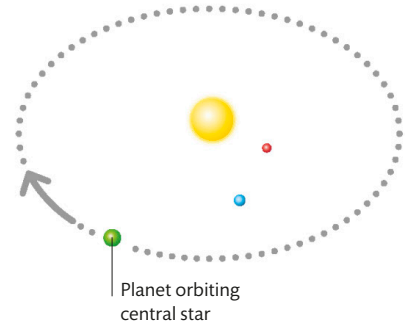
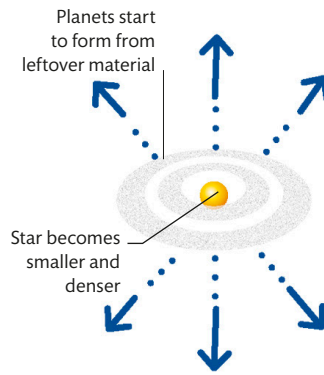
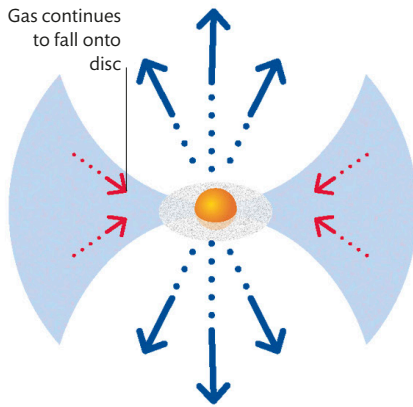
How a protostar forms

Stars form in dark clouds of gas and dust (see pp.94–95) dense enough to block out light. Starbirth begins when the cloud is disturbed, possibly by shockwaves from a supernova explosion (see pp.118–119), so that clumps of gas and dust begin to pull together under their own gravity. Gravity does the rest.

STAR SIZES AND NUMBERS

There are many more low-mass stars than high-mass stars in the Universe. This is partly because far fewer big stars are born, but also because very big stars have very short lives, so they do not consume fuel and emit light for long. As this graphic shows, for each star of more than 10 solar masses, there are approximately 10 stars of 2–10 solar masses and 50 stars of 0.5–2 solar masses. There are even more red dwarf stars (see pp.88–89) – 200 for each star over 10 solar masses.





4 T Tauri star

After up to a million years, the central temperature of the protostar reaches 6,000,000°C (10,800,000°F). At this point, hydrogen fusion reactions start and the new star, called a T Tauri star, begins to shine.

5 Pre-main sequence star

After up to 10 million years, the T Tauri star shrinks and grows denser. Material from the disc and the remaining envelope flows into the star, or disperses into space. Planets start to form in the disc.

6 Planetary system created

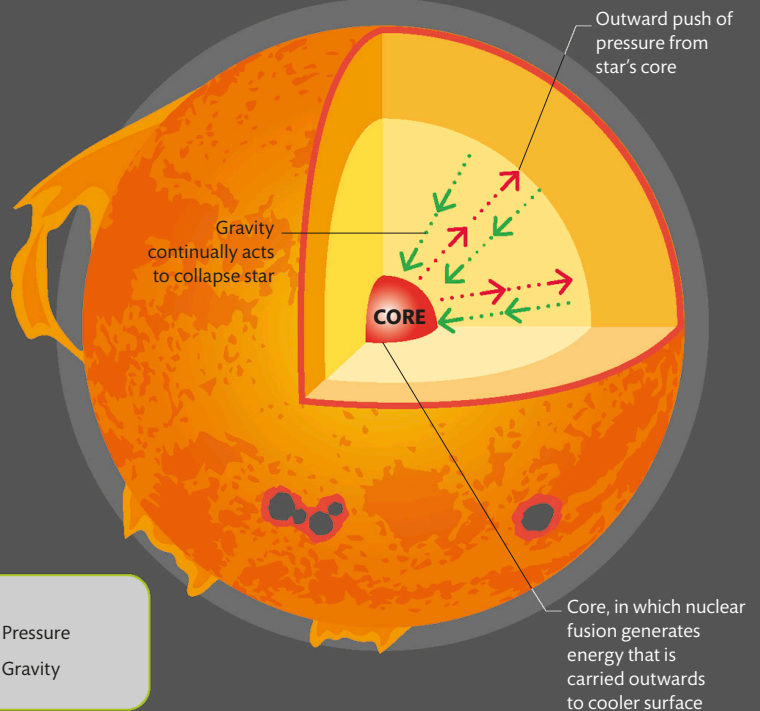
The star is now a main-sequence star (see pp.88–89), and planets orbiting the star have fully formed. A planetary system like this typically lives for approximately 10 billion years.

Forces in stars

Once low- and medium-mass stars have begun to fuse hydrogen into helium, they enter the main sequence (see pp.88–89). At this point in the life of a star, the forces inside them – gas pressure emanating from the core and the opposing force of gravity – are balanced. Stars on the main sequence can go on shining steadily for approximately 10 billion years.

Balanced forces

The balance between outward-pushing pressure and inward-pulling gravity in a star is known as hydrostatic equilibrium. It is this balance that keeps a star stable.



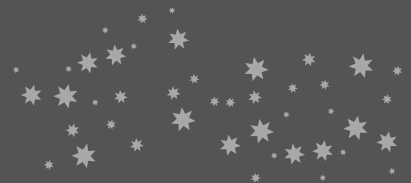
WHEN DID THE FIRST STARS APPEAR?

The first stars appeared around 200 million years after the Big Bang. A further billion years passed before galaxies began to proliferate.

KEY

.....→ Pressure
.....→ Gravity

STARS ARE THOUGHT TO FORM IN THE UNIVERSE AT A RATE OF ABOUT 150 BILLION A YEAR



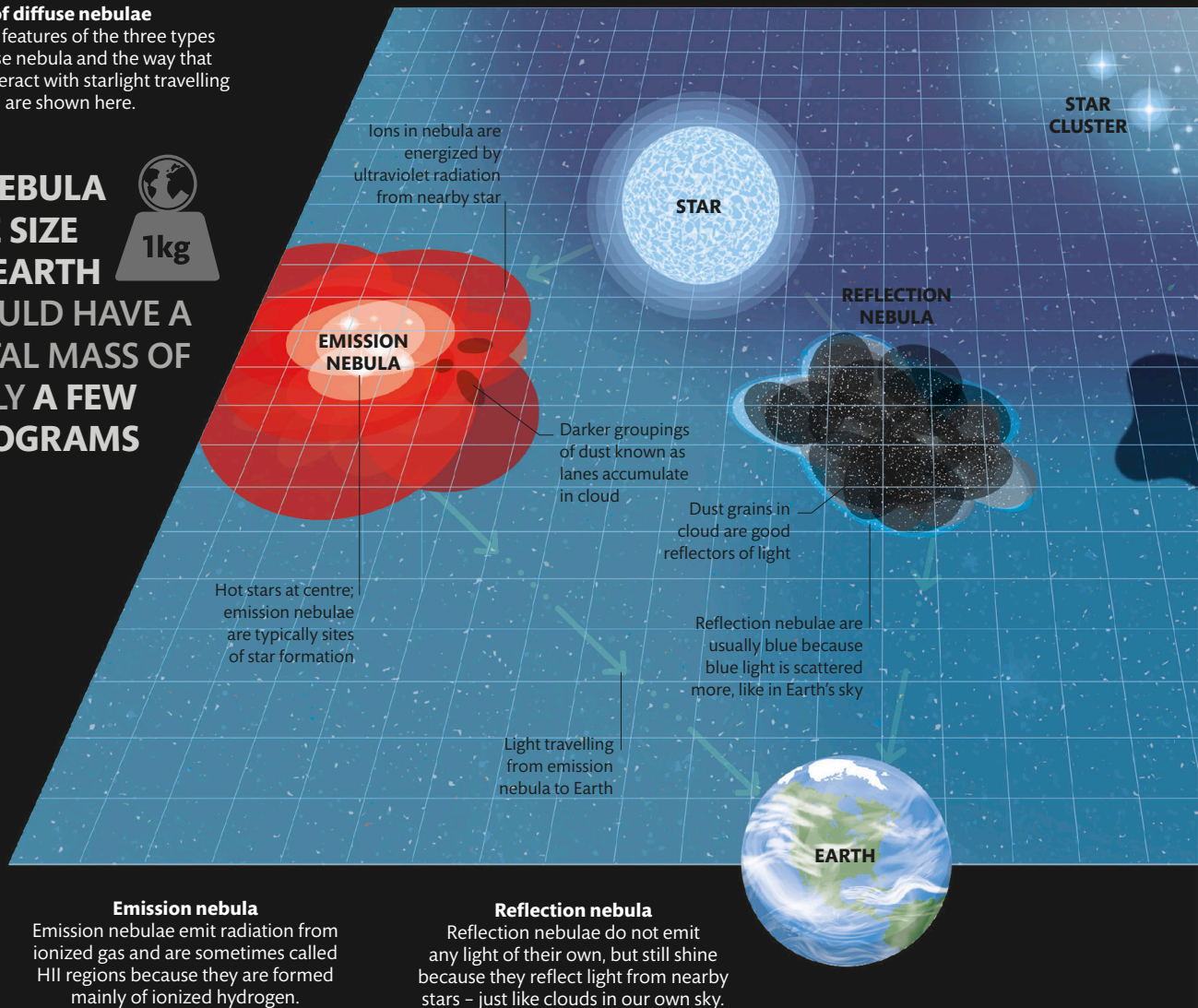
Nebulae

Nebulae are giant clouds in space made of dust and gas. A nebula forms when the sparse material of space clumps together through mutual gravitational attraction. The very densest of nebulae become nurseries for stars.

Types of diffuse nebulae

The key features of the three types of diffuse nebula and the way that they interact with starlight travelling to Earth are shown here.

A NEBULA THE SIZE OF EARTH WOULD HAVE A TOTAL MASS OF ONLY A FEW KILOGRAMS



Emission nebula

Emission nebulae emit radiation from ionized gas and are sometimes called HII regions because they are formed mainly of ionized hydrogen.

Reflection nebula

Reflection nebulae do not emit any light of their own, but still shine because they reflect light from nearby stars – just like clouds in our own sky.

**HOW LARGE CAN
A NEBULA GET?**

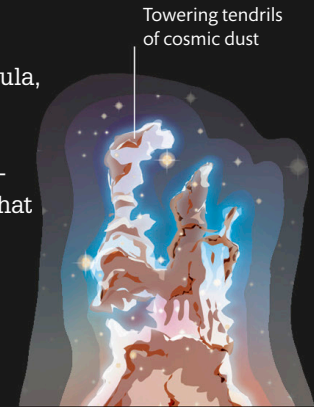
The Tarantula Nebula, located approximately 170,000 light-years from Earth in the Large Magellanic Cloud, stretches for over 1,800 light years.

Stellar nurseries

Many nebulae are the birthplaces of stars. The most famous is perhaps the Eagle Nebula, where stars are born inside the towering clouds known as the “pillars of creation”. These towers, which are each several light-years long, are formed of dense materials that have resisted evaporation by the radiation emitted from nearby young stars.

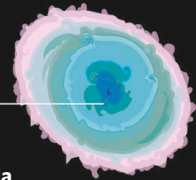
Pillars of creation

This dramatically shaped part of the Eagle nebula contains hundreds of newly forming stars in its pillars.

**Nebulae around dying stars**

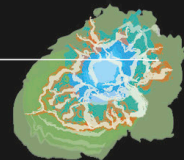
Planetary nebulae and supernova remnants are also types of nebula, and are both created by dying stars. Confusingly, a planetary nebula has nothing to do with planets. It is a shell of gas thrown out by a smaller star as it nears the end of its life. This shell is then ionized by the star's ultraviolet radiation, causing the nebula to glow brightly. A supernova remnant forms when a massive star explodes violently in a supernova, sending a vast cloud of ionized dust and gas out into space.

Blue glow caused by hot helium

**Planetary nebula**

The Ring Nebula in the constellation Lyra is a remnant of the final stages in the life cycle of a low-mass star.

Pale orange areas show cold dust left from supernova

**Supernova remnants**

The Crab Nebula in the constellation Taurus is the remnant of a massive star that exploded in 1054 CE.

Light travelling from star cluster to Earth

DARK NEBULA

Dark nebula absorbs light emitted by a star cluster, preventing it reaching Earth

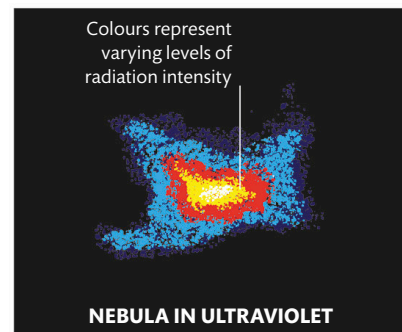
Dark nebula

Dark, or absorption, nebulae are clouds of dust like reflection nebulae; they only look different because they block out the light from behind.

FALSE-COLOUR IMAGING

Objects in space, including nebulae and galaxies, often emit radiation that our eyes cannot detect because it lies outside the visible spectrum. To make pictures of these objects, astronomers use software to assign colours that we can see to the various intensities of radiation they have measured. These pictures are called false-colour images.

Colours represent varying levels of radiation intensity



Star clusters

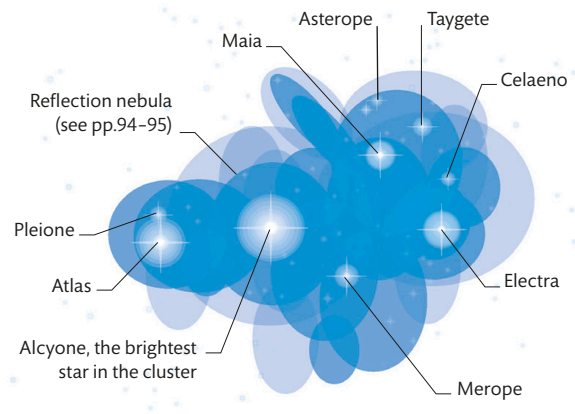
Some stars belong to groups called clusters. Open clusters are loose groups of young stars formed from the same cloud of gases and dust. Globular clusters are giant balls of ancient stars.

Types of cluster

Open clusters are mostly just a few tens of millions of years old. The stars are often slightly bluish because they contain remnants of the original cloud. Globular clusters are almost as old as the universe, and the gas and giant stars have long since gone. They can include groups of thousands or millions of stars, bound together by gravity.



THE PLEIADES STAR CLUSTER APPEARS ON THE NEBRA SKY DISC, DATING FROM 1600 BCE



Open cluster

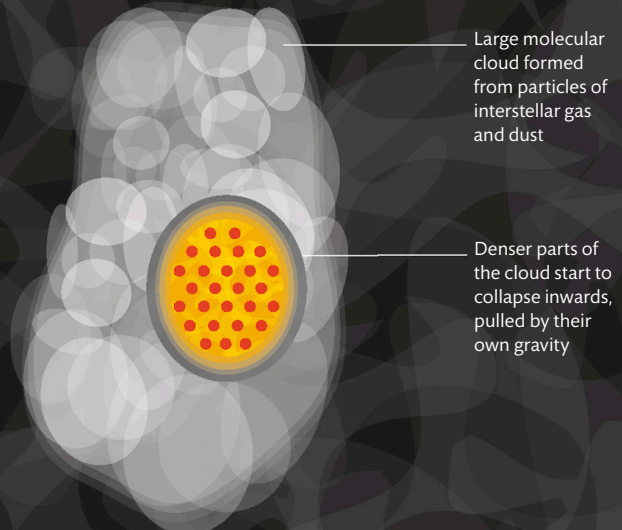
The Pleiades is an open cluster of around 3,000 stars that is visible to the naked eye. It is less than 100 million years old and dominated by nine young, bright blue giant stars. The brightest stars of the Pleiades are named after the Seven Sisters of Greek mythology, along with their parents Atlas and Pleione.

HOW DO WE WORK OUT THE AGE OF STAR CLUSTERS?

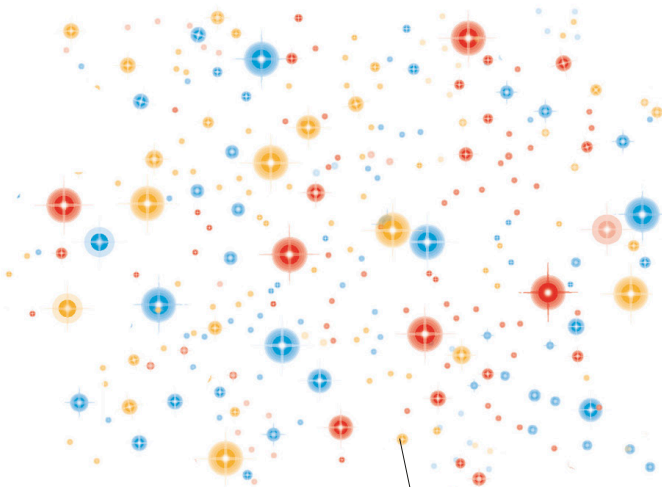
Astronomers can tell the age of a star cluster from its mix of stars of different kinds. The older a cluster, the greater the number of stars that have evolved into giants.

How an open cluster develops

Stars are born in large clouds of molecular gas, so they inevitably form in clusters, since these clouds contain the matter needed to create thousands of stars. Clusters contain stars of all types, from relatively cool red dwarfs to massive blue giants. Most clusters last only a few hundred million years as the biggest stars die out and many loosely bound small stars are pulled away by other gravitational attractions.



1 Stars are born Very young stars, which are known as protostars, form where dense concentrations of gas collapse under gravity in a molecular cloud. This can be triggered by the shockwave from a supernova (see pp.118–19).



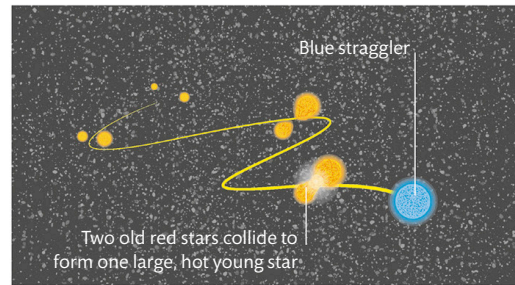
Globular cluster

The stars in the vast Omega Centauri cluster are over ten billion years old. It is over 16,000 light years away, yet its ten million stars shine so brightly together that the cluster is visible to the naked eye, looking like a single star.

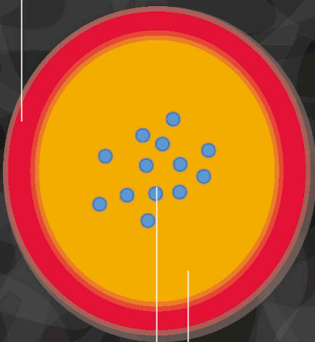
Unusually for globular clusters, Omega Centauri includes stars of various ages, most of which are small yellow and white stars

BLUE STRAGGLERS

Globular clusters are mostly so ancient that they should not contain young blue stars. Yet some of them do. "Blue stragglers" are thought to form because stars are so closely packed near the centre of the cluster that old red stars can collide. When they do, the collision forms a new, high-mass blue star and pumps hydrogen into its core.



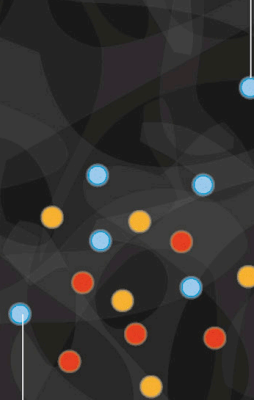
Region of electrically charged hydrogen made to glow by ultraviolet radiation from hot blue stars



Young stars form and begin converting hydrogen to helium through nuclear fusion

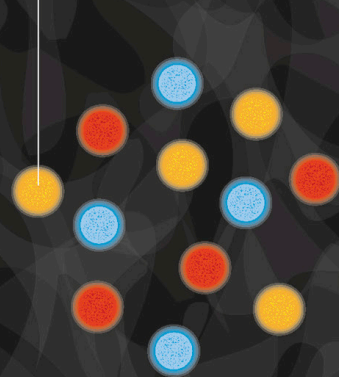
Bubble cleared of gas by powerful stellar winds from newly formed star

Some become runaway stars, tugged away by encounters with other clusters and clouds



Most stars are pulled to centre of cluster by gravity

Open clusters are populated by stars from across the spectrum of mass, colour, and brightness



2 The cloud clears

The brightest new stars are hot, massive, and short-lived O-type, B-type, and A-type stars (see pp.88–89). They emit powerful winds of particles that clear away surrounding gas and create a bubble.

3 Young cluster

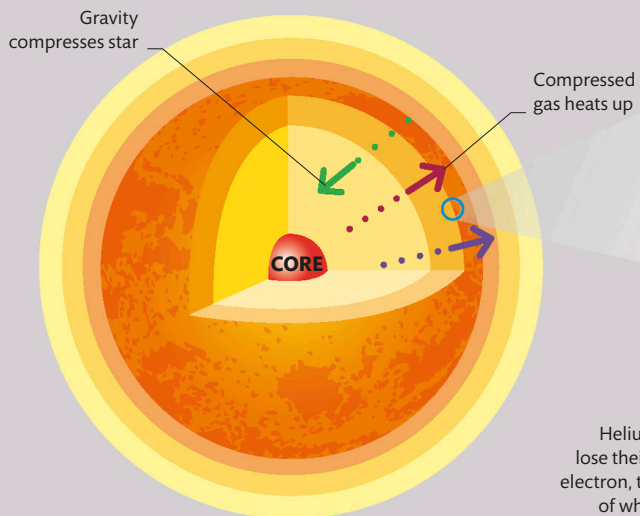
After gas remnants are blown away, gravity still holds the cluster loosely together. Some runaway stars are pulled away by gravitational interactions with other clusters and clouds of gas.

4 Older cluster

The stars that remain in the cluster move around. Gradually, all of the stars escape and disperse into space over a period of a few hundred million years.

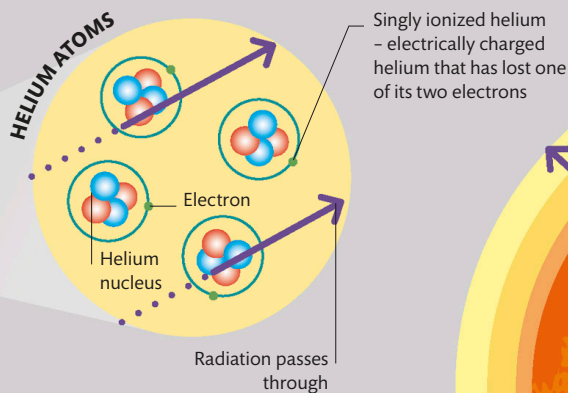
1 How a cepheid pulsates

Some stars pulsate because radiated energy is continually trapped then released by the helium in a particular layer of the star. This occurs because the helium atoms change between two different electrically charged states.



2 Helium becomes transparent

As the helium atoms heat up, they lose one of their two electrons. This makes the gas more transparent to radiation, allowing energy to escape.



Variable stars

A variable star is a star that changes in brightness, on a timescale ranging from fractions of a second to years. With extrinsic variable stars, the variation is an illusion caused by the star's rotation or another star or planet moving in front of it. With intrinsic variable stars, such as cepheids (shown below), the change is due to physical changes in the star itself.

KEY

.....→ Pressure → Gravity → Radiation

Helium atoms lose their second electron, the effect of which traps radiated energy

Pressure rises

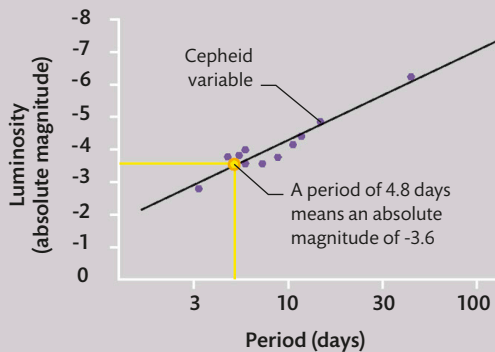
Electron moves freely

3 Helium becomes opaque

The helium atoms lose their remaining electron, which makes the gas more opaque. This means that the energy travelling from the star's core is trapped so pressure inside the star rises and the star swells.

Cepheid variables

Cepheids are a type of variable star that exhibit a relationship between their period (the time it takes to brighten, dim, and brighten again) and their luminosity (see p.89). The brighter a Cepheid is, the longer its period, so timing its period shows how bright it is. Comparing the period to the star's apparent brightness means that it is possible to work out how far it is away from Earth.



UP TO 85 PER CENT OF
ALL STARS ARE PART OF
MULTIPLE-STAR SYSTEMS



Period-luminosity relationship

When you know the period of a Cepheid, you can use a period-luminosity chart to work out its absolute magnitude. An equation is then used to calculate its distance from Earth.



Multiple and variable stars

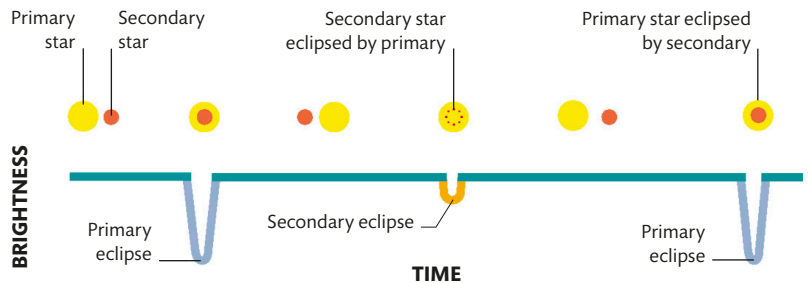
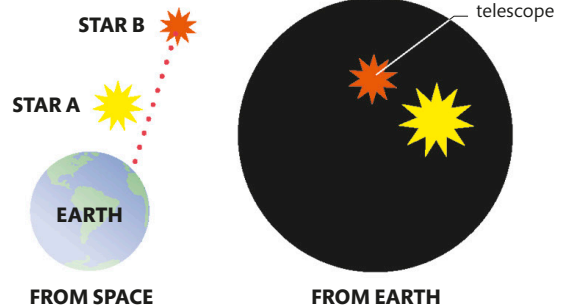
It may look as if all the points of light in the sky are lone stars like our Sun. In fact, over half are in pairs called binaries and two-thirds of the rest are in even bigger groups. More than 150,000 stars are variable stars that fluctuate in brightness.

Binary stars

Binaries are two stars orbiting a common centre of mass, known as a barycentre. The brighter star of the two is called the primary. Multiple groups include three or more stars circling around each other in complex patterns. Some binary stars are too far apart to have much of a gravitational effect on each other. Others are so close that one star can draw mass from the other – sometimes so much that it becomes a black hole (see pp.122–123).

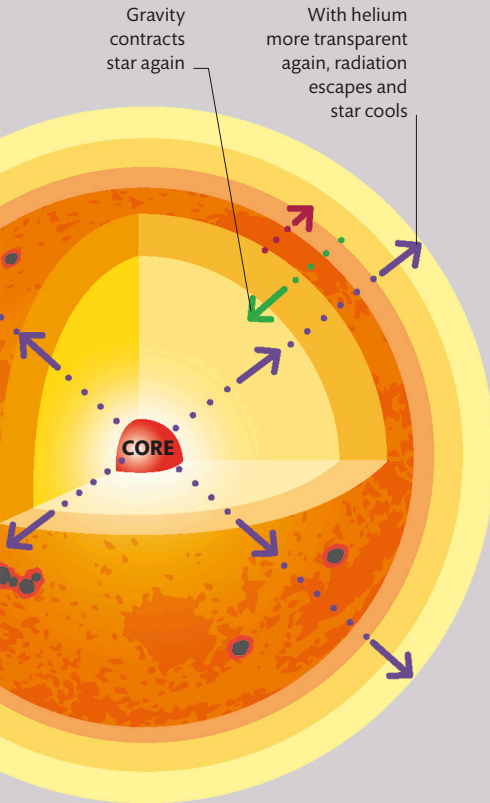
Optical doubles

Two stars that are not together, like true binaries, but just in the same line of sight from Earth are called optical doubles. They may not look like it, but the two stars are often at vast distances from each other.



Eclipsing binary stars

These are two stars whose orbits are in line as seen from Earth, so that one regularly passes in front of the other, causing the combined brightness to dip. This repeated eclipse can give the illusion that the star is flashing on and off.



4 Radiation released

As the star expands, the helium cools. Helium atoms revert back to their singly ionized state, which allows radiation to escape. Pressure inside the star drops and gravity pulls the star in again, recompressing the gas.

HOW MANY STARS CAN EXIST IN A SYSTEM?

The star systems AR Cassiopeiae and Nu Scorpii are the only known examples of septenary star systems (systems of seven stars).

There are several sexenary systems.

Between the stars

The space between the stars, known as the interstellar medium (ISM), contains gas and dust that plays an important role in the evolution of stars. Within the ISM are distinct regions, characterized by differences in temperature, density, and electric charge.

In the densest diffuse clouds, known as H I regions, the constituent hydrogen atoms are entirely neutral; temperatures in these regions range from -170°C (-280°F) to 730°C ($1,340^{\circ}\text{F}$)

Interstellar gas

Around 99 per cent of the ISM is gas, mostly hydrogen. On average, each cubic centimetre of the ISM is occupied by only one atom (compared to 30 million trillion molecules per cubic cm in the air we breathe). But over the vastness of space that is enough to form visible clouds. These are either cold clouds of neutral hydrogen or hot clouds of charged hydrogen near young stars. Helium is the second most common element, but many others are also found in very small quantities as individual atoms or in molecules.

COLD INTERSTELLAR MEDIUM

In coolest parts of cold
interstellar medium,
temperatures are as low
as -260°C (-440°F)

6 Red giant

5 An ageing medium-mass star uses up its fuel and collapses, scattering dust and gas to form new clouds. On average, a third of the matter drawn into stars goes back into interstellar space.

**AROUND 15 PER CENT
OF ALL THE VISIBLE
MATTER IN THE
MILKY WAY IS
INTERSTELLAR
GAS AND DUST**



1 Clouds form

Interstellar clouds form from the gas and dust particles expelled by dying red giants (see pp.110–11). Diffuse clouds are the least dense of these clouds, dominated by neutral or charged (ionized) hydrogen.

2 Dense regions form

2 Dust grains and gas particles in diffuse clouds may gather together because of their mutual gravitational attraction.

DIFFUSE CLOUD

Some regions of the ISM are heated to temperatures up to about 10,000 °C (18,000 °F)

CORONAL INTERSTELLAR GAS

Many galaxies are surrounded by a vast, tenuous halo or corona of hot ionized gas

Supernova

6 An ageing high-mass star becomes a supergiant, which eventually goes supernova (see pp.118–19). The debris from the explosion adds new material to the ISM.

5 Protoplanetary system

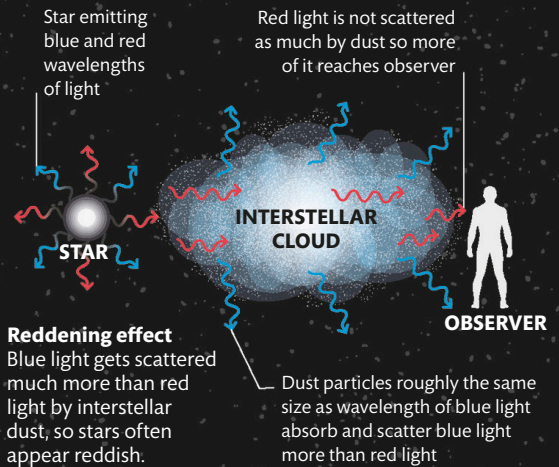
5 When a new star forms, dust collects in a disc rotating around the star, then clumps together to form planets.

PLANET ORBITING STAR



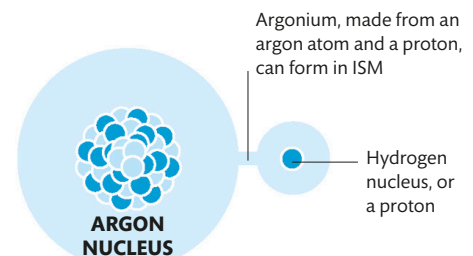
Interstellar dust

Interstellar dust is mostly atomic soot belched out by stars. It is composed of tiny grains containing silicates (compounds of oxygen and silicon), carbon, ice, and iron compounds. These irregularly shaped microscopic grains are 0.01–0.1 micrometres (millionths of a metre) in diameter and are warmer than the surrounding gas. Interstellar dust accounts for around 1 per cent of the total mass of the ISM.



NOBLE COMPOUNDS

It was thought that some gases, called noble gases, could not combine with other elements. But in the extreme conditions of the ISM, the impossible can happen. Helium has been detected joining with hydrogen, and argon can combine with hydrogen to form the compound argonium.



Detecting cold clouds
Neutral hydrogen atoms (protons) in HI regions can be detected when their electrons spontaneously reverse their direction of spin.

21-cm-long waves of radiation emitted when electrons reverse their direction of spin; these waves can be detected by radio telescopes

3 Forming clumps

Molecular clouds are much smaller and denser than diffuse clouds. Within them, hydrogen forms molecules, and dust and gas combine to produce clumps that form pre-stellar cores.

MOLECULAR CLOUD
PRE-STELLAR CORE

4 Star formation

In places, clumps gather together enough material and grow big enough to create the interior pressure needed to form stars.

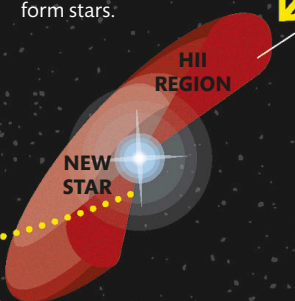
In a cloud where stars form, called an HII region, heat from stars ionizes much of cloud's hydrogen; electrons emit light as they shift energy levels, making cloud glow

IS INTERSTELLAR SPACE A VACUUM?

In parts, the ISM is the closest thing to a vacuum. Densities in coronal interstellar gas are far lower than laboratory vacuums on Earth, but nowhere in space is totally empty.

The ISM cycle

Stars are formed out of the ISM. Then, when they die, much of their matter, including new elements created inside stars and in stellar explosions, is expelled back into the ISM to start the cycle again.



Exoplanets

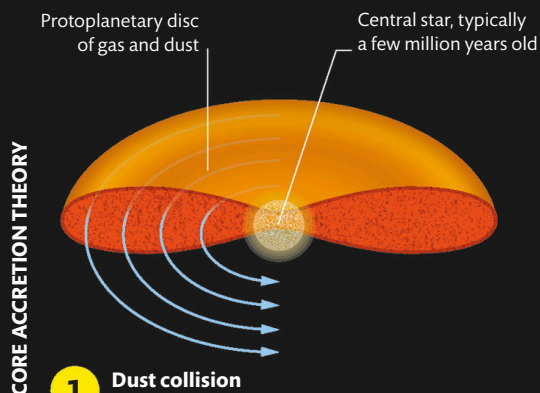
Our Sun is not the only star to be orbited by other planets. Since 1995, when the first exoplanets were discovered, over 4,000 more have been found. With ongoing missions dedicated to the search, the total is increasing all the time.

How planets form

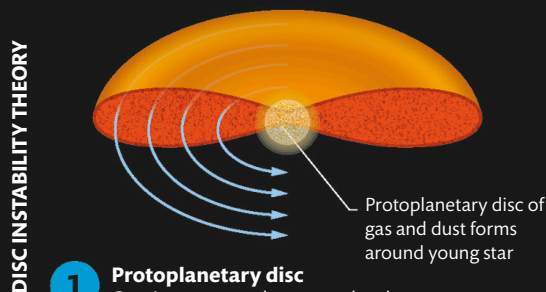
There are two theories about how planets form: one to do with building from the top down, the other from the bottom up. In the bottom-up theory, core accretion, planets slowly form through collisions between increasingly large pieces of debris in the disc of gas and dust surrounding a young star. In the top-down theory, disc instability, giant planets can result when large clumps of gas form in the disc of material surrounding a young star.



51 PEGASI B WAS THE FIRST EXOPLANET DISCOVERED ORBITING A STAR LIKE OUR SUN



- 1 Dust collision**
Swirling dust grains in a protoplanetary disc collide, forming bigger and bigger clumps. This process creates mini planets called planetesimals.



- 1 Protoplanetary disc**
Gravity starts to draw together loose clumps of gas in the cooler, outer parts of the protoplanetary disc.

Types of exoplanet

As astronomers learn more about exoplanets, they group them into loose categories, comparing them with the planets in the Solar System and with Earth in particular. Some categories depend on a planet's mass, such as super-Earths and mega-Earths. Some of the smaller exoplanets may be covered in oceans and are known as water worlds. Other categories depend on how closely the planet orbits the star. Hot Jupiters and hot Neptunes are gas giants in tight, fast orbits around their stars. Exo-Earths, such as TOI 700d, discovered in 2020, are perhaps the most interesting due to their potential habitability.



Hot Jupiter

These gas giants have a similar mass to Jupiter, but are much closer to their host stars and are therefore much hotter.



Chthonian planet

This is the solid remnant core of a gas giant. The atmosphere has been stripped away due to its close proximity to its star.



Mega-Earth

First used for Kepler-10c in 2014, "mega-Earth" refers to a rocky planet with at least 10 times Earth's mass.



Super-Earth

These can be up to 10 times the size of Earth. The first super-Earth with water in its skies was found in 2019.



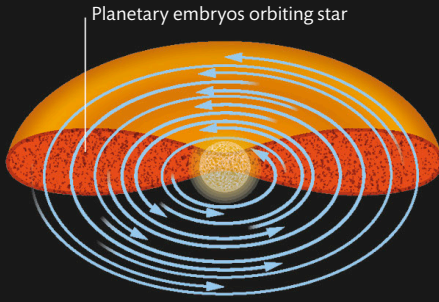
Water world

A terrestrial planet with surface water or a below-surface ocean, the first, GJ 1214B, was discovered in 2012.



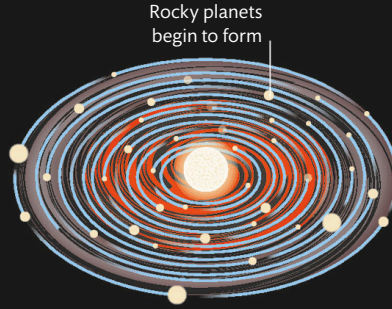
Exo-Earth

This is a planet with a size and mass similar to Earth and located within the habitable zone of its star.



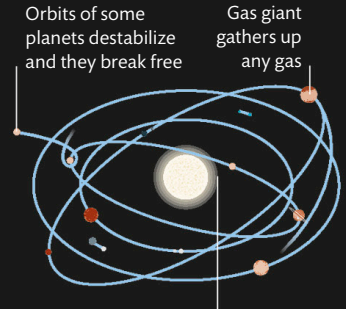
2 Planetary embryos form

The planetesimals grow, to form the embryos of planets, and begin to move in orbits around the central star.



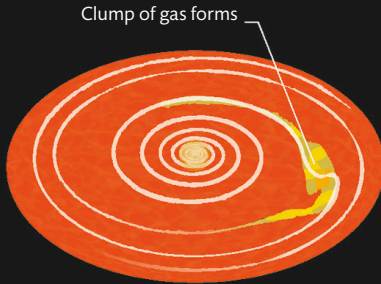
3 Rocky planets form

Close to the star, heavier metallic elements condense and violent collisions can lead to the creation of rocky planets.



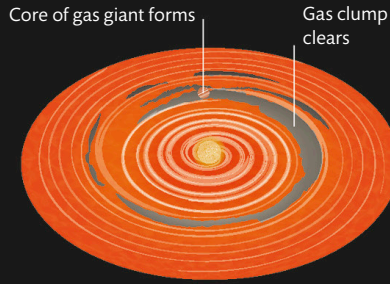
4 Gas giants created

Further out, cooler temperatures allow hydrogen and helium to condense to form gas giants.



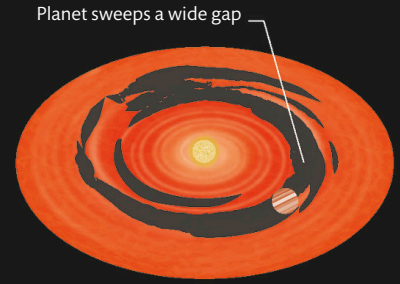
2 Separating out

A clump containing enough gas to form a giant planet cools rapidly. It shrinks and becomes denser.



3 Core forming

Dust grains are drawn in by the gravity of the massive gas clump. They fall to the centre to form the core of a giant planet.



4 Planetary sweeper

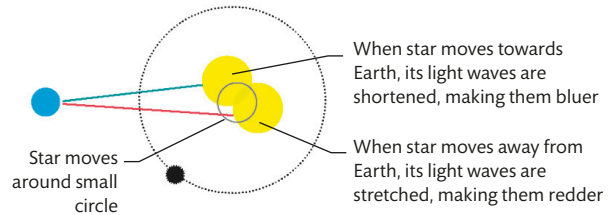
The new planet sweeps through the disc, clearing a wide path and growing as it gathers in gas and dust on its way.

Detecting exoplanets

Exoplanets are tiny compared to their parent star and are often hidden by the star's glare, since they emit no light of their own. Only a few giant exoplanets have been photographed directly, a technique called direct imaging. Most are detected indirectly using methods called transit photometry and radial velocity. Just under 100 exoplanets have been discovered by a process called gravitational microlensing, which involves a chance alignment of a nearby star with planets and a distant star. The exoplanets reveal themselves as they bend the distant star's light a bit like a lens.

Radial velocity method

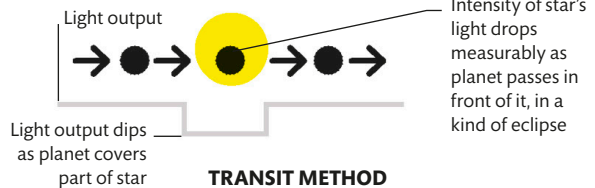
When a large planet orbits a star, its gravitational pull causes the star to move around a small circle so that the light waves it emits change colour.



RADIAL VELOCITY METHOD

Transit photometry method

When a planet passes in front of the star it orbits, we cannot see the planet directly but the star dims slightly, which can be measured.



TRANSIT METHOD

KEY

● Earth

● Star with potential planet orbiting it

● Exoplanet

Finding other Earths

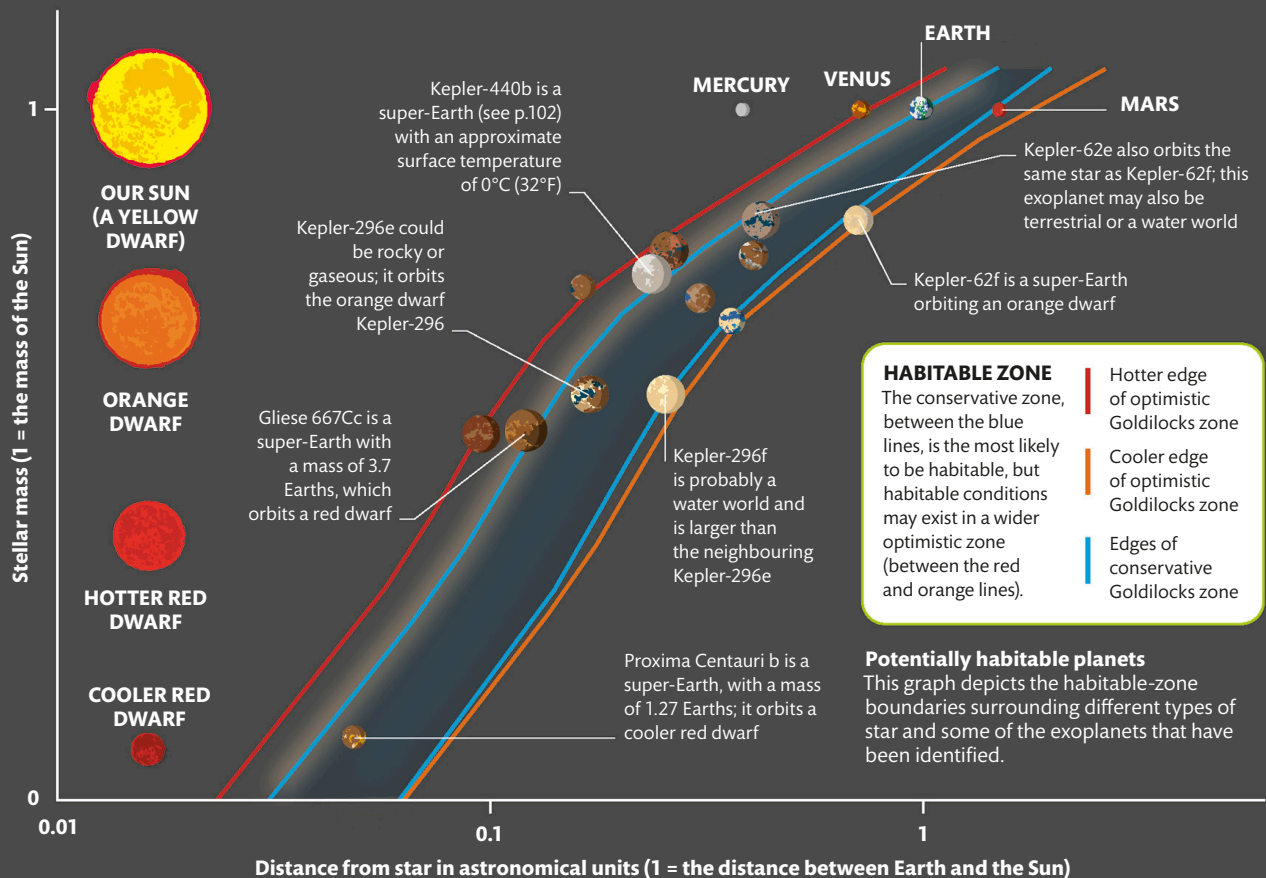
Ever since astronomers discovered the first exoplanet in 1995, they have been hunting for planets similar to Earth. The search centres on areas around stars known as habitable zones, where conditions may be right for life. So far, more than 50 planets have been discovered in habitable zones.

The Goldilocks zone

Water is essential for life – so the habitable zone around every star is the zone where the temperature is right to maintain liquid surface water. This zone is sometimes called the Goldilocks zone, because it is neither too hot nor too cold, like the porridge that Goldilocks favoured in the fairy tale. If the planet is too hot, water will boil away; if it is too cold, then water will freeze. In a system containing a big, hot star, the habitable zone is much further out than it is in a system with a small, cooler star.

CAN EXOPLANETS ORBIT MORE THAN ONE STAR?

Astronomers have found over 200 double stars with planets. Kepler-64 was the first quadruple-star system found with a planet orbiting two of the stars.





What makes a planet habitable?

When searching for potentially habitable planets, astronomers look mostly for rocky planets, like Earth. Once a likely exoplanet has been identified, research efforts focus on establishing other factors that might make it a prime candidate for life, such as a moderate surface temperature and liquid surface water. NASA's Transiting Exoplanet Survey Satellite (TESS), which launched in 2018, scans the sky for planets in the habitable zone. It is the successor to the Kepler Space Telescope (see pp.186–87), which detected over 2,600 exoplanets.



Temperature

This must be moderate to keep water liquid. If it is too cold, chemical reactions may be too slow to sustain life.



Surface water

Liquid surface water would make life very likely, but it is possible that water underground may support life.



Stable sun

The nearest star must remain stable and shine steadily in order for life to evolve on a rocky planet.



Elements

The building blocks of life, including carbon, oxygen, and nitrogen, need to be present.



Spin and tilt

A tilted spin axis stops extremes of temperature. Planets that do not spin can be very hot on the side facing the star.



Atmosphere

An atmosphere traps warmth, shields the surface from harmful radiation, and stops gases from escaping.



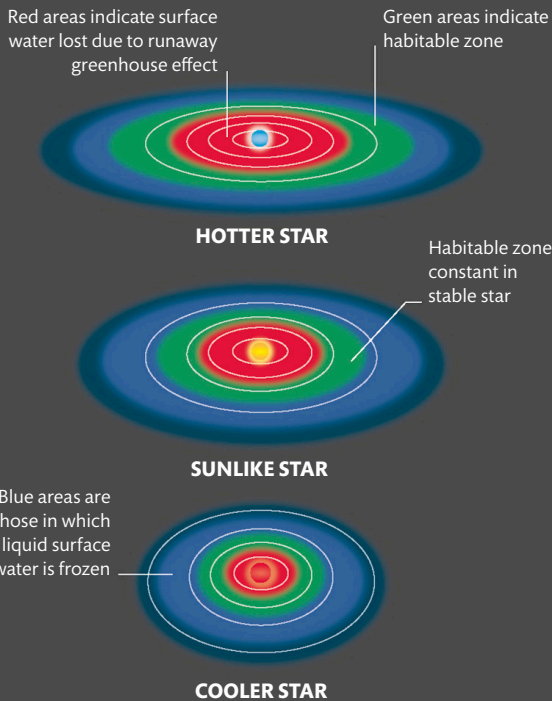
Molten core

A molten core can create a magnetic field that shields life from some of the radiation coming from outer space.



Sufficient mass

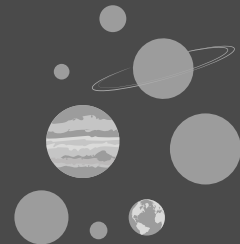
Without sufficient mass, a planet will not have enough gravity to hold on to its water or its atmosphere.



Changing zones

The location of a star's habitable zone (in green) compared with areas that are too hot (red) and too cold (blue) depends upon a star's luminosity and size. The edges of habitable zones change as stars age, especially as they reach the ends of their lives.

THE KEPLER-90 SYSTEM CONTAINS 8 EXOPLANETS, THE SAME NUMBER AS IN OUR SOLAR SYSTEM



THE MOST EARTH-LIKE PLANET

The exoplanet Kepler-1649c is 300 light-years from Earth. NASA described it as the "most similar to Earth in size and estimated temperature" out of the thousands of exoplanets discovered by the Kepler space telescope. It was discovered on 15 April 2020.



Earth



Kepler-1649c

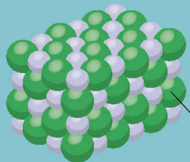
The four ingredients

There are thought to be four ingredients that make life possible: water, energy, organic chemicals, and time. Without these, life is unlikely to be supported in other worlds.



WATER

SODIUM CHLORIDE



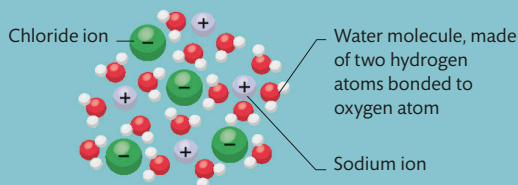
1 Dissolving salt

When dissolving sodium chloride (salt), water molecules pull the sodium and chloride ions apart, breaking their bonds.

Chemical reactions

Almost all the processes that make up life on Earth involve chemical reactions – and most of those reactions require a liquid to break down substances so they can move and interact freely. The best and most abundant liquid for this purpose is water.

Lattice structure of salt, comprising positively charged sodium and negatively charged chloride ions



2 Solution formed

After the bonds are pulled apart, the sodium and chloride ions are surrounded by water molecules to form a solution.

TIME



Sufficient time

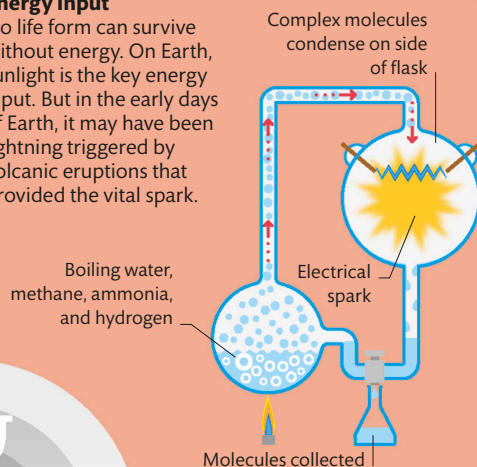
The journey from single-celled organisms to complex life requires a time period of billions of years.

ENERGY



Energy input

No life form can survive without energy. On Earth, sunlight is the key energy input. But in the early days of Earth, it may have been lightning triggered by volcanic eruptions that provided the vital spark.



The Miller-Urey test

In 1952, an experiment simulated lightning to prove that, given enough energy, complex organic molecules can form from simple inorganic materials.

HYDROGEN



OXYGEN



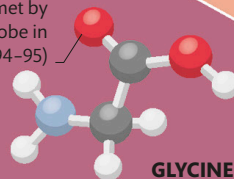
NITROGEN



CARBON



Amino acid glycine, as found on a comet by the Rosetta probe in 2016 (see pp.194–95)



GLYCINE

Carbon-based chemicals

Organic chemicals are the basis of life on Earth. Yet these molecules, including complex amino acids, are abundant elsewhere in the Universe, too, detectable in huge quantities in nebulae and identified in meteorites that hit Earth.

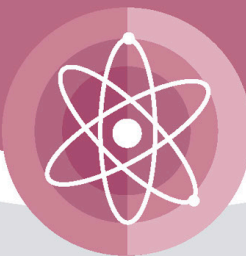
1 Inorganic ingredients

As on Earth, complex mixtures of gases in a planet's atmosphere could provide the sources of life's principal elements: carbon, hydrogen, oxygen, and nitrogen.

2 Simple organic molecules

Charged with enough energy, atoms of carbon, hydrogen, and other elements can combine to form the organic molecules (some carbon compounds) needed for life, such as amino acids.

ORGANIC MOLECULES



LIFE ON EARTH
MAY STRETCH

BACK 4.3 BILLION YEARS



Is there life in the Universe?

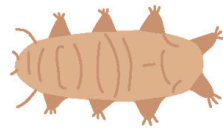
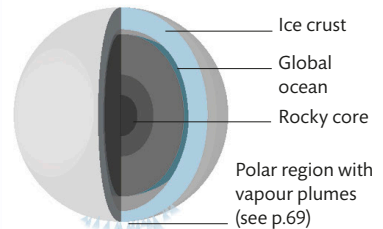
Life on Earth may be unique, but most scientists think this is unlikely. The Universe is so vast that it is possible that the conditions that created life on Earth could also exist elsewhere.

Ingredients for life

Scientists who search for life in space, known as astrobiologists, believe that there are four key ingredients for life to begin: water, organic molecules, energy, and time. Water is essential for life, because it dissolves chemical nutrients for organisms to eat, transports vital chemicals inside cells, and enables cells to remove waste. The right chemical ingredients are also needed to make life possible. Carbon is top of the list, because its unique ability to form bonds with itself and other elements enables it to form the complex molecules crucial to life, such as proteins and carbohydrates.

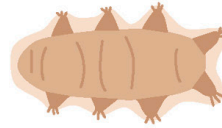
ENCELADUS

Since discovering extremophiles, astrobiologists have renewed their search for signs of life in more extreme places in the Solar System, including Saturn's moon Enceladus. In 2011, plumes of water vapour containing salts, methane, and complex organic molecules were found erupting through its icy surface from oceans beneath.



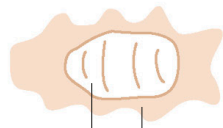
Active state

In its active state, a tardigrade can eat, grow, move, fight, and reproduce.



Anoxobiosis

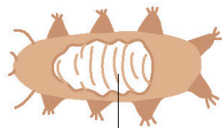
If the water in its environment loses oxygen, a tardigrade puffs up and becomes turgid.



Inner cuticle | Outer shell

Encystment

To adapt to harsh environments, it makes itself a tough outer shell and retracts within a cuticle.



Dry "tun" forms

Anhydrobiosis

In very dry conditions, it shrivels into a dry ball (tun) and survives by consuming special proteins.

Extremophiles

On Earth, microbes have been discovered in hostile places such as in boiling water around vents in the ocean floor. These extremophiles, lifeforms that thrive in extreme conditions, suggest that life can develop in a huge range of environments. The tardigrade, an aquatic micro-animal, can enter various states to adapt to its surroundings (see left). In one of these states, anhydrobiosis, a tardigrade stops its metabolism and shrivels up. In this state, a tardigrade can even survive in the harsh conditions of outer space.

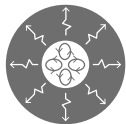
How stars age

Most stars seem unchanging, but over billions of years they are born, age, and finally die. We can see examples of nearly all the different stages of stellar evolution by studying the stars in our galaxy and beyond.

A star's life story

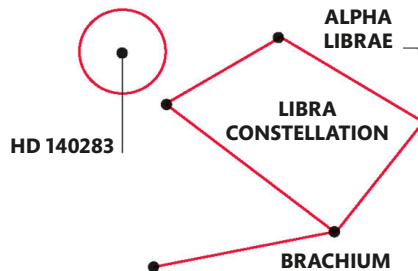
After a new star enters the main sequence (see pp.88–89), it steadily converts hydrogen to helium through nuclear fusion in its core. This can take place for billions of years, with outward pressure from fusion balancing the inward force of gravity. When a star has used up all the hydrogen in its core, it enters the last stages of its life. What happens then depends on a star's mass. Low-mass stars shrink and are thought to fade into black dwarfs; medium-mass stars expand into red giants, then collapse as white dwarfs; and high-mass stars become supergiants, then explode in supernovae.

6,000,000°C
(11,000,000°F) IS THE
APPROXIMATE TEMPERATURE
AT WHICH NUCLEAR FUSION
BEGINS IN A STAR'S CORE



OLDER THAN THE UNIVERSE?

HD 140283, described as the “Methuselah” star, is one of the Universe’s oldest known stars. In 2000, scientists calculated its age as 16 billion years, but that was impossible because the Universe itself is only 13.8 billion years old. In 2019, the star’s age was recalculated as about 14.5 billion years, but with a margin of error of 800 million years. Whatever its precise age, HD 140283 is very old indeed.



HOW LONG DOES A STAR SPEND ON THE MAIN SEQUENCE?

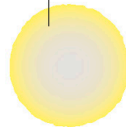
Stars spend 90 per cent of their lives on the main sequence, converting hydrogen to helium. The final stages of their lives occur relatively quickly.

Red dwarfs are very low-mass stars and the smallest, coolest stars on the main sequence



- 1 Low-mass star**
The lower the mass of a star, the longer it stays on the main sequence before entering its final stages.

Star on the main sequence

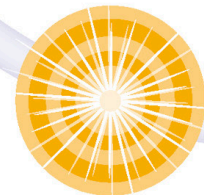


Medium-mass star, which has almost exhausted the hydrogen in its core



- 1 Medium-mass star**
Stars such as the Sun burn slowly over around 10 billion years before they use up the hydrogen in their cores.

Main sequence
A star enters the main sequence once the hydrogen fusion that makes it shine begins. Its life after that can go one of three ways, depending on its initial mass.



- 1 High-mass star**
The most massive stars burn bright and fast, some for as little as 20 million years.



Star starts to decrease in size as inward-pulling gravity is now stronger than outward-pushing pressure

Small, dim star gradually fades

A low-mass star might last 80 billion years before collapsing to form hypothetical black dwarf



2 Fusion ceases
All the hydrogen in the star's core has been used up, so it converts the hydrogen in its atmosphere to helium and starts to collapse.

3 Shrinking down
The star cannot generate enough heat in its core to burn helium, so it cools, starts to fade, and continues to decrease in mass.

4 Brown dwarf
Gravity continues to shrink the star so that it is a fraction of its former size. It becomes dimmer, glowing only at infrared wavelengths.

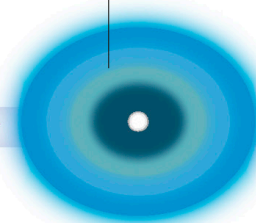
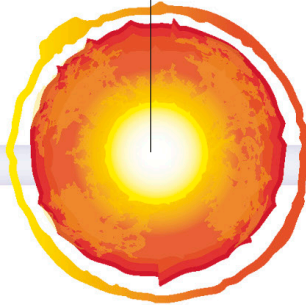
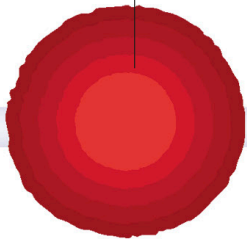
5 Black dwarf
This is the hypothetical end point for low-mass stars, as no star has had enough time to cool down enough to become a black dwarf.

Hydrogen fusion begins in shell outside core

Helium dumped in core, which swells

Planetary nebulae often look spectacular but are relatively short-lived

White dwarfs can reach temperatures exceeding 100,000 K



2 Subgiant stage
In this phase, the star swells as it burns helium in its core and the shell outside the core becomes hot enough to fuse hydrogen.

3 Red giant stage
The star expands dramatically as the hydrogen fusion in the shell creates extra helium to fuel the core.

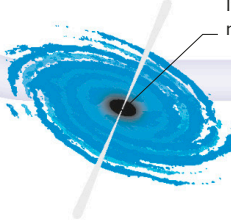
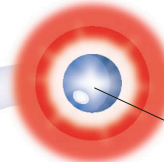
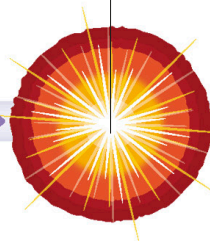
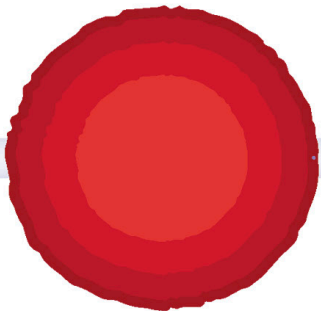
4 Planetary nebula
Eventually the star throws out its shells of gas to form a glowing envelope of clouds called a planetary nebula.

5 White dwarf
As the clouds of the planetary nebula dissipate, the old core remains and becomes a bright white dwarf.

Supernovae can be seen across Universe

If mass of star is between 1.4 and 3 solar masses, remnant collapses into neutron star

If remnant of star is over 3 solar masses, it forms a black hole



2 Supergiant stage
Supergiants and hypergiants are the biggest stars in the Universe.

3 Supernova
When a supergiant has used up all of its fuel, it collapses and explodes in a supernova.

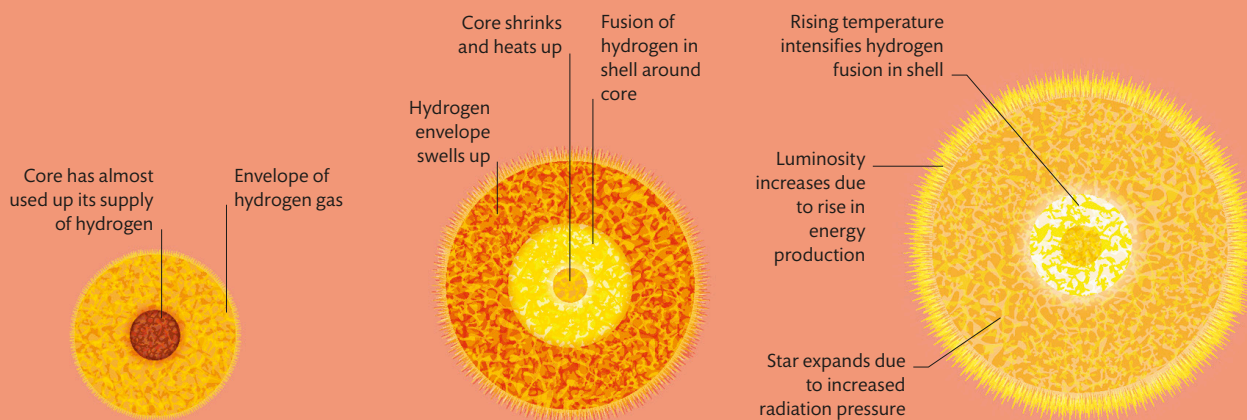
4 Collapsing star
Depending on its mass, the remnant collapses into a neutron star or a black hole.

Red giants

When low- and medium-mass stars use up all the hydrogen in their cores, they reach the end of their long, stable lives on the main sequence. They quickly swell into red giants for the last phases of their lives, becoming much bigger and brighter but glowing a coolish red.

The life cycle of a red giant

Low- and medium-mass stars like the Sun spend 90 per cent of their lives on the main sequence of the H-R diagram (see pp.88–89). But eventually they use up the hydrogen in their cores, which contract and grow hotter until the surrounding shell of hydrogen gets so hot that fusion starts. This makes them swell hugely to become red giant stars approximately 100 million–1 billion km (62 million–620 million miles) in diameter – that is, 100 to 1,000 times the size of the Sun today.



1 Exhausted core

By now, the star's core has used most of its fuel supply of hydrogen nuclei. There is more hydrogen in the layers outside the core, but it is not hot enough to fuse. The core starts to contract, getting hotter and denser.

2 Shell ignition

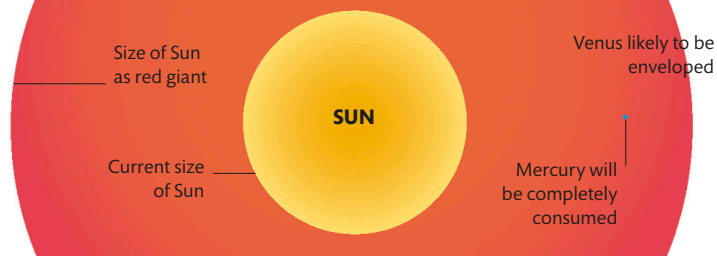
Hydrogen in the layer over the shrinking core falls inwards and heats up. It begins to fuse into helium in a shell surrounding the old core. Driven by this new burst of heat, the star swells quickly.

3 Bigger and brighter

Medium-mass stars grow rapidly to become red giants. Hydrogen fusion in the shell around the core dumps helium in the core, which also swells. The boost in energy production makes the star glow brightly.

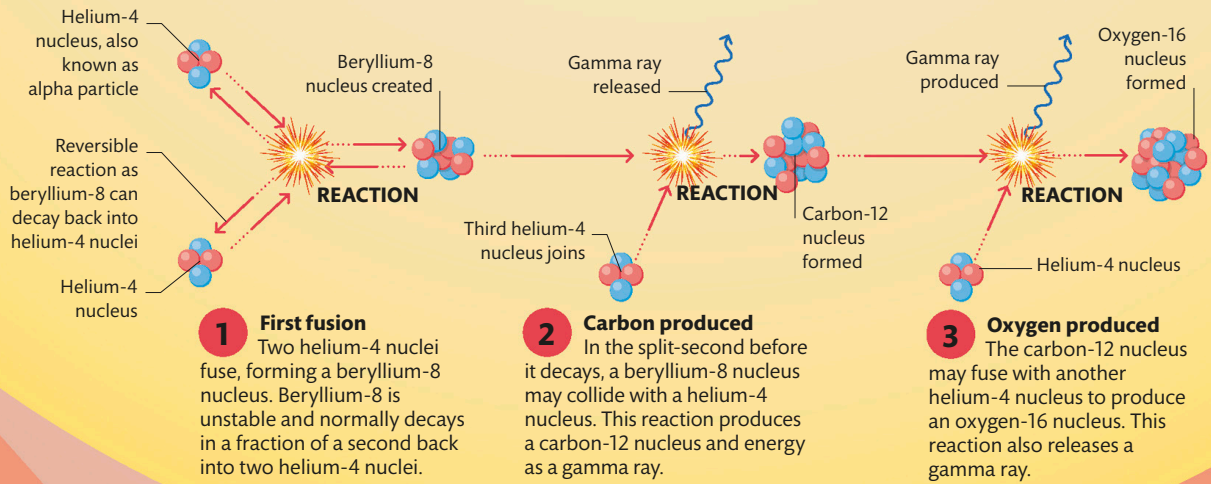
THE SUN AS A RED GIANT

In about 5 billion years, the Sun will exhaust its hydrogen, begin helium fusion, and turn into a red giant star. As the Sun expands, its outer layers will engulf Mercury, probably Venus, and possibly Earth as well.



WHAT MAKES A RED GIANT RED?

A star's colour depends on its surface temperature, which for a typical red giant is about 5,000°C (9,000°F). This puts the brightest light it emits in the orange-red part of the spectrum.



HELIUM FUSION, OR THE TRIPLE-ALPHA PROCESS

Core becomes denser and hot enough to start helium fusion

Outer surface heats up again as star shrinks

Hydrogen fusion ceases in the shell, star shrinks, and luminosity reduces; radiation pressure from core makes shell swell

Helium fusion starts in shell

Carbon core

Fusion of hydrogen in shell reinvigorated

Luminosity rises as star swells

4 Helium flash

Helium fusion (see above) begins suddenly with the "helium flash" in which energy production shoots up 100 billion times. Pressure from the core causes the hydrogen shell to expand, reducing its energy output. This makes the star shrink and become dimmer.

5 Final burn-out

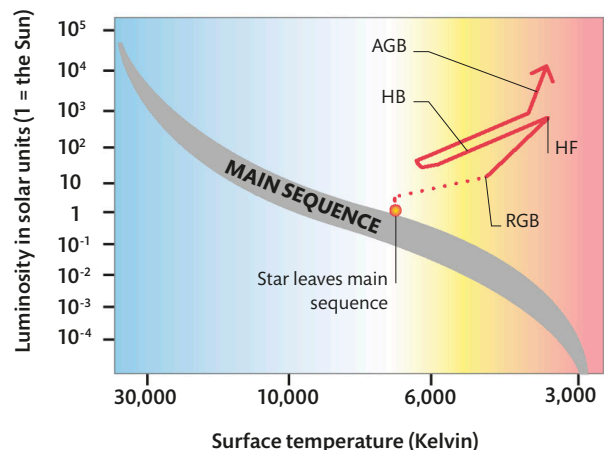
Once all the helium in the core has been used, hydrogen and helium fusion continue in two shells around the core. Helium produced in the hydrogen shell fuels the helium shell. Both shells heat up and the star brightens and expands.

Changing temperature and brightness

Once they leave the main sequence, low- and medium-mass stars take a zigzag path across the H-R diagram. Each change in direction across the chart reflects the change in temperature and brightness at different phases in the star's life. The three key stages are: the red-giant branch (RGB); the horizontal branch (HB) that begins with the helium flash (HF); and the final, "asymptotic giant" branch (AGB) when the star has developed a carbon-oxygen core.

Zigzag path across the H-R diagram

The zigzag path of a star with a mass similar to the Sun shows how it first grows cooler even as it gets bigger and brighter, then heats up, before finally cooling again.

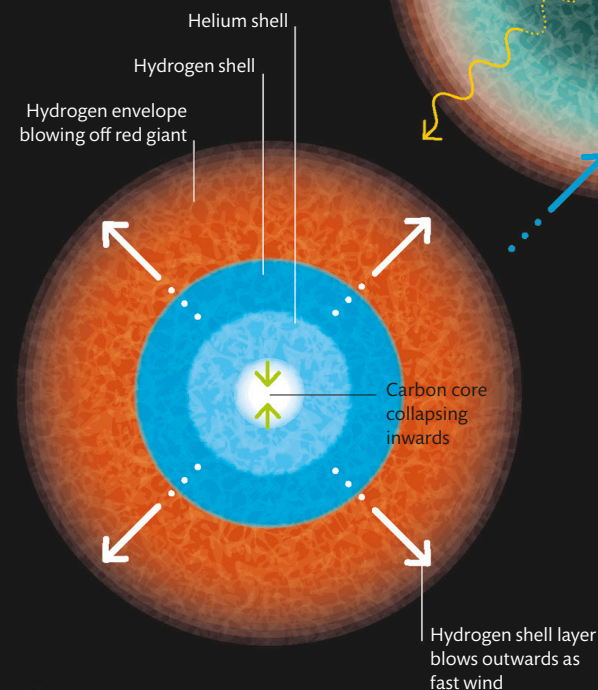


Planetary nebulae

Massive stars explode and low-mass stars fade away, but medium-mass stars become planetary nebulae, which gradually dim and leave behind white dwarfs. They are among the most colourful objects in the Universe.

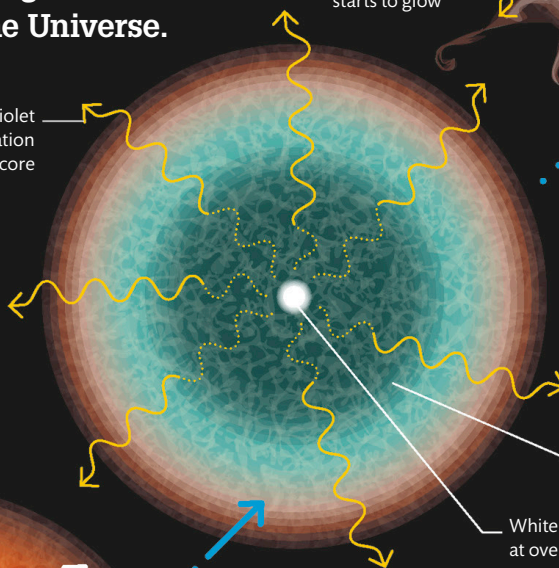
A dying star

In the last stages of its life, a red giant (see pp.110–11) expands at such a speed that gas in its outer layers escapes the star's gravity. This gas is also pushed away by pressure exerted from the star's core.



1 Shell blown out
The old red giant's core collapses, and it expels its burned-out hydrogen shell. The resulting stellar wind blows the shell out in all directions into space, travelling at a speed of approximately 70,000 kph (43,500 mph).

Ultraviolet radiation from core



2 Radiation emitted
The star's core contracts further, becoming a bright white dwarf. Intense ultraviolet radiation emitted from the core begins to travel outwards, heating the previously ejected hydrogen. The fast stellar wind catches up with the envelope, creating a shockwave.

Knots form in areas more resistant to shockwave

Ultraviolet radiation ionizes shell of gas, which starts to glow

Gaseous tentacles form in envelope

3 Thin shell formed
The shockwave interacts with the hydrogen and bunches it up into a shell. Gaseous tentacles form in the envelope when expanding hot gas pushes into cooler gas. Ultraviolet light from the brightening central star ionizes the shell and causes it to glow.

How a planetary nebula forms

A planetary nebula forms gradually and continually evolves. First, the layers surrounding a red giant's burned-out core are blown off as a fast wind. Then the star's exposed core sends out a brilliant glow of mostly ultraviolet radiation. This is invisible to the naked eye, which is why planetary nebulae do not look as bright as they really are unless false-colour imaging is used (see pp.94–95). Despite the name, planetary nebulae have nothing to do with planets; the name arose in the 18th century, when observers thought some of the first to be discovered resembled the disc shape of a planet.



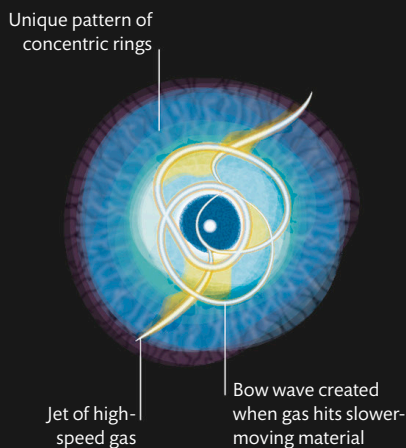
Planetary nebula shapes

There is a huge variety of planetary nebula shapes, but most can be grouped into three types: spherical, elliptical, and bipolar. The variety arises partly because their appearance seems to change when they are viewed from different angles, a phenomenon called the projection effect. But the shape may also be affected if the central star has a companion, planets, or a magnetic field.



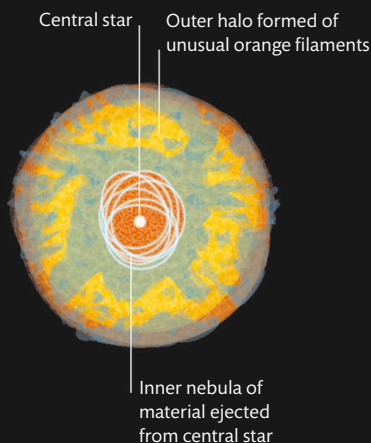
Butterfly Nebula (bipolar)

This bipolar planetary nebula has two lobes shaped like butterfly wings. Bipolar nebulae such as this are thought to have formed when the central object is a binary system, in which only one star survives.



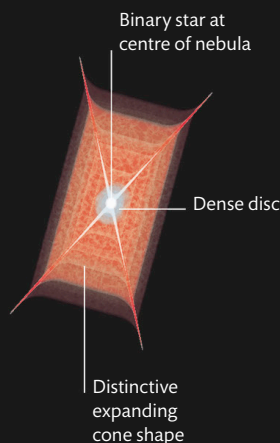
Cat's Eye Nebula (elliptical)

The bright central part of the beautiful Cat's Eye nebula is incredibly complex. It is surrounded by a faint halo of rings, blown out like bubbles at intervals of 1,500 years.



NGC 2392 (spherical)

This nebula reminds some people of a head surrounded by a furry hood. The central structure is due to overlapping bubbles of ejected material.



Red Rectangle Nebula (bipolar)

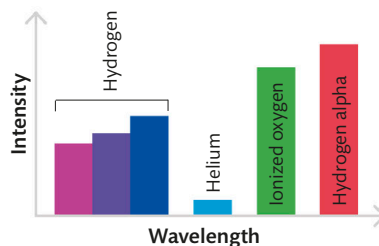
It is not understood how this uniquely shaped nebula formed. One idea is that gas ejected from its binary star sent out shockwaves after hitting a thick dust ring.

HOW LONG DO PLANETARY NEBULAE LAST FOR?

Planetary nebulae exist for only a short time – tens of thousands of years compared with the star's lifespan of several billion years.

CHEMICAL COMPOSITION

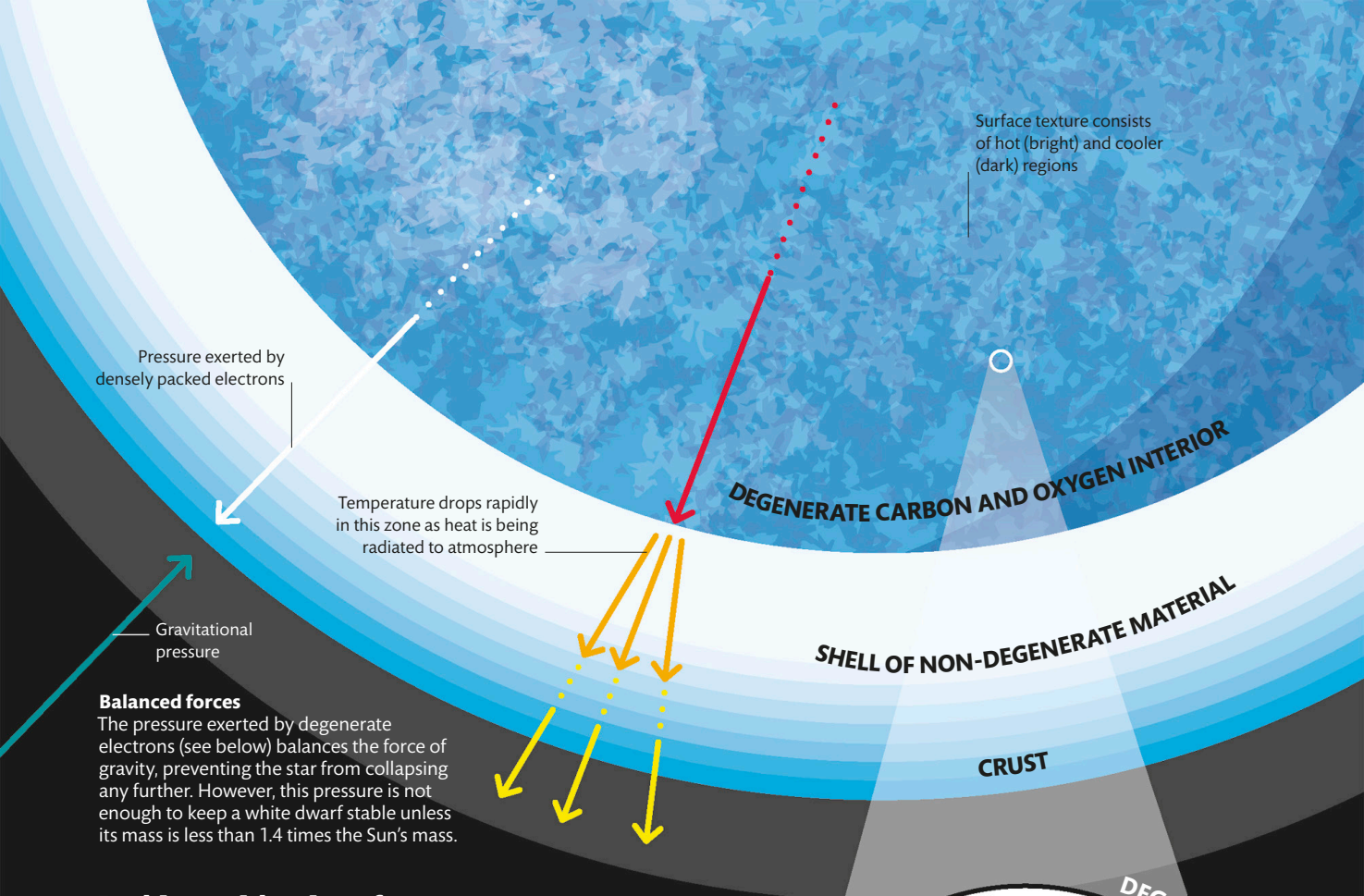
The chemical nature of planetary nebulae is revealed by the spectra of their light (see pp.26–27). A strong red emission line, called a hydrogen alpha line, is caused by a hydrogen electron falling from its third- to second-lowest energy level. This is what often gives planetary nebulae a reddish colour. A strong green line reveals a type of ionized oxygen formed only in the low-density setting of a planetary nebula.



TYPICAL PLANETARY NEBULA EMISSION SPECTRUM

IN 5 BILLION YEARS,
THE SUN WILL
BECOME A FAINT
PLANETARY NEBULA





Pressure exerted by densely packed electrons

Temperature drops rapidly in this zone as heat is being radiated to atmosphere

Surface texture consists of hot (bright) and cooler (dark) regions

DEGENERATE CARBON AND OXYGEN INTERIOR

SHELL OF NON-DEGENERATE MATERIAL

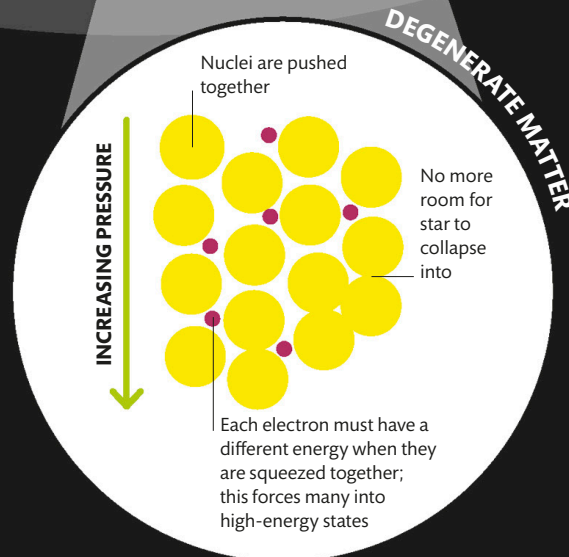
CRUST

Balanced forces

The pressure exerted by degenerate electrons (see below) balances the force of gravity, preventing the star from collapsing any further. However, this pressure is not enough to keep a white dwarf stable unless its mass is less than 1.4 times the Sun's mass.

Inside a white dwarf

As red giants (see pp.110–11) use up their remaining fuel, they expel their outer layers as planetary nebulae (see pp.112–13), leaving only a tiny, hot core, known as a white dwarf. This remnant slowly cools down and fades. A white dwarf's atmosphere is composed mostly of either hydrogen or helium. The interior, composed mostly of carbon with some oxygen, is thought to crystallize as the white dwarf cools. Since a diamond is crystallized carbon, a white dwarf can be compared to an Earth-sized diamond.



How degenerate matter forms

Without fusion, there is no energy source to counteract the inward pull of gravity. Gravity crunches the electrons and nuclei much closer than they would be in atoms. This is called a degenerate state. Degenerate matter exerts a pressure that stops the star from collapsing.

White dwarfs

Sun-sized stars that formed soon after the birth of the Universe end their lives as white dwarfs. They are little bigger than Earth, yet contain about the same amount of matter as the Sun.



Crust thought to be only
50 km (30 miles) thick

Atmosphere of almost pure
hydrogen or helium

White dwarfs and planetary destruction

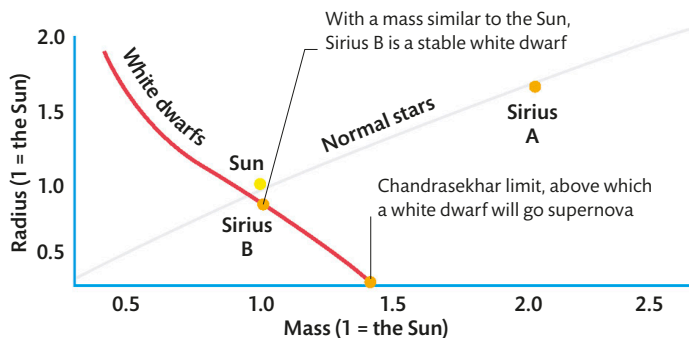
In 2014, scientists working on K2, the second space mission involving the Kepler Space Telescope (see p.187), believed they had observed a white dwarf in the process of destroying its own planetary system. The intense gravitational pull of the white dwarf appeared to be tearing fragments of its companion planet away into orbit around the star, creating a debris disc. A simulation of the process over the course of 120 days, after the planet first begins to feel the significant effects of the star's intense gravitational force, is shown here.

WHO FIRST DETECTED A WHITE DWARF?

Telescope maker Alvan Clark discovered one in 1863. He realized that the slight "wobble" in the star Sirius's orbit was caused by the gravity exerted by a white dwarf companion.

THE CHANDRASEKHAR LIMIT

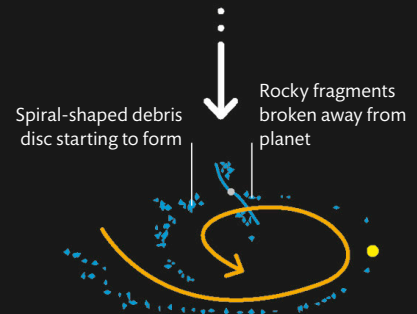
Indian-American astrophysicist Subrahmanyan Chandrasekhar discovered that there is a limit to the amount of mass a white dwarf can have and remain stable, supported by its degenerate matter. Beyond that limit, approximately 1.4 times the mass of the Sun, a white dwarf collapses and explodes as a supernova (see pp.118–19), leaving behind either a neutron star or a black hole.



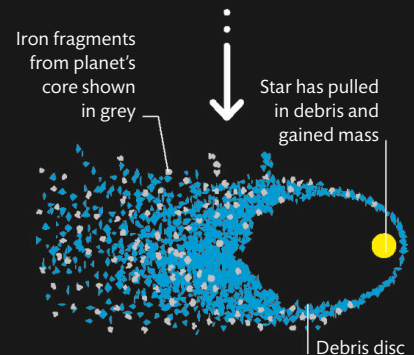
Companion planet

White dwarf star

1 After 1 day
The gravitational force of an Earth-sized white dwarf pulls mass from an orbiting planet. The blue line shows a stream of rocky fragments being drawn away from the planet.



2 After 16 days
More rocky fragments are pulled from the exterior of the planet, which is now rotating faster and faster. A debris disc can be seen forming around the star.



3 After 120 days
The planet has completely broken up. The inner part of the debris disc is almost entirely rocky, with iron from the planet's core littered over a wider field. The star has accumulated mass from the destroyed planet.

Blue supergiant

Blue supergiants, such as Rigel A, are much larger than the Sun but far smaller than red supergiants. These stars have only just come off the main sequence (see pp. 88–89), and are incredibly luminous.

Red giant

The brightest star in the constellation Taurus, Aldebaran has a radius 44 times that of the Sun. It is only about 65 light-years from Earth, so it appears as the 14th brightest star in the night sky.

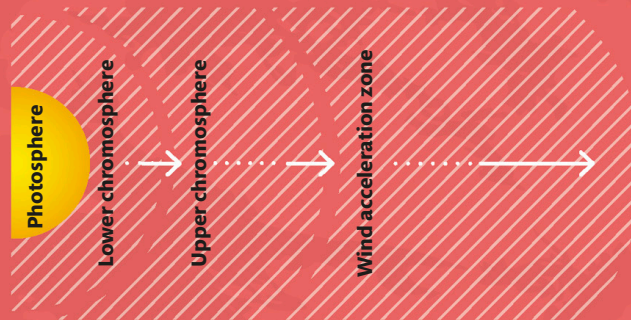
Blue hypergiant

The Pistol Star is one of the brightest stars in the Milky Way, with a luminosity (see p.89) approximately 1.6 million times that of the Sun. It is classified as a blue hypergiant and also thought to be a luminous blue variable star, an as yet not fully understood phase in the life cycles of massive stars.

Many supergiants start off blue, but then expand via yellow to red, getting cooler all the time

Atmosphere of Antares

Antares is around 700 times larger than the Sun, but an international effort concluding in 2020 showed that its atmosphere, including the lower and upper chromosphere and wind acceleration zones, reaches out 2.5 times further than that.



ATMOSPHERE LAYERS

Supergiants

Supergiants are stars of very high mass that have used up the last of their hydrogen fuel and entered the final phases of their lives. At this point in their evolution, they have swollen to enormous sizes.

The life cycle of a supergiant

Like red giants, supergiants fuse helium when they have depleted their supply of hydrogen before starting to fuse the heavier elements. As they fuse these elements, the stars swell to become supergiants. Supergiants do not live for as long as red giants, though, with the largest stars having the shortest lifespans. Supergiants end their lives in spectacular fashion, exploding in supernovae (see pp.118–19).

Comparing sizes

Here, various star sizes are compared with the radius of the Sun. Blue stars tend to be smaller than their red counterparts but are just as bright due to their higher surface temperatures.

**THE PISTOL
STAR RELEASES
AS MUCH ENERGY IN
20 SECONDS AS THE
SUN DOES IN A YEAR**





Stars such as the Pistol Star are rare and exhibit dramatic variations in their brightness

Pollux has a radius around nine times greater than the Sun

Bellatrix has a luminosity 9,211 times that of the Sun

Sun is a main sequence star classified in the "G" spectral class (see pp.88–89)

Orange giant

Pollux is an orange giant star in the constellation Gemini. It is approximately 30 times brighter than the Sun and is the closest giant star.

Blue giant

Bellatrix, in the constellation Orion, has a radius 5.75 times that of the Sun. In time, it may evolve into an orange giant.

Yellow dwarf

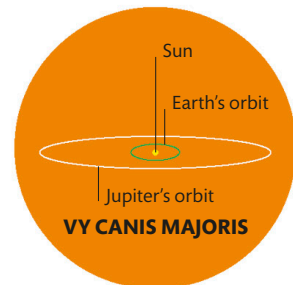
Although it appears tiny next to the giants and supergiants, our Sun is actually a slightly larger than average star.

HOW BIG CAN A STAR GET?

There does seem to be an upper limit to a star's mass. Collapsing protostars over 150 times more massive than the Sun generate so much energy that they blow themselves apart.

HYPERGIANTS

Hypergiants are the biggest stars in the Universe. It is difficult to determine which is the largest, because they have vague edges and they continually lose mass as their surfaces are blown away by powerful stellar winds. Among the biggest are VY Canis Majoris and UY Scuti, both approximately 1,400 times as big as the Sun.

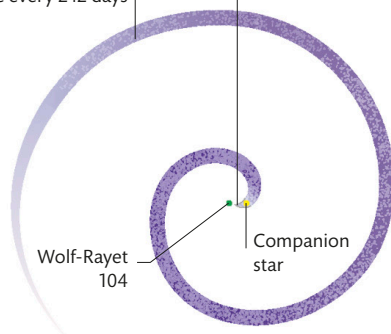


Wolf-Rayet stars

Wolf-Rayet stars are extremely hot and at an advanced stage of evolution. With masses around 10 times that of the Sun, they fuse heavy elements in their cores, which stops them collapsing under their own immense mass. This generates intense heat and radiation that propels strong stellar winds out at speeds of up to 9 million kph (5.6 million mph). These winds make Wolf-Rayet stars lose mass at a high rate. Many of them have companion stars, and their interacting stellar winds create a distinctive spiral of dust.

Hot dust is carried around by the orbital motion of the two stars, completing a rotation once every 242 days

Dust forms at shock front where stellar winds of the two stars collide



Spiral outflow

Dust formed when the intense stellar winds from Wolf-Rayet 104 and its companion star collide is blown outwards and swirled into a spiral by the two stars orbiting each other.

Exploding stars

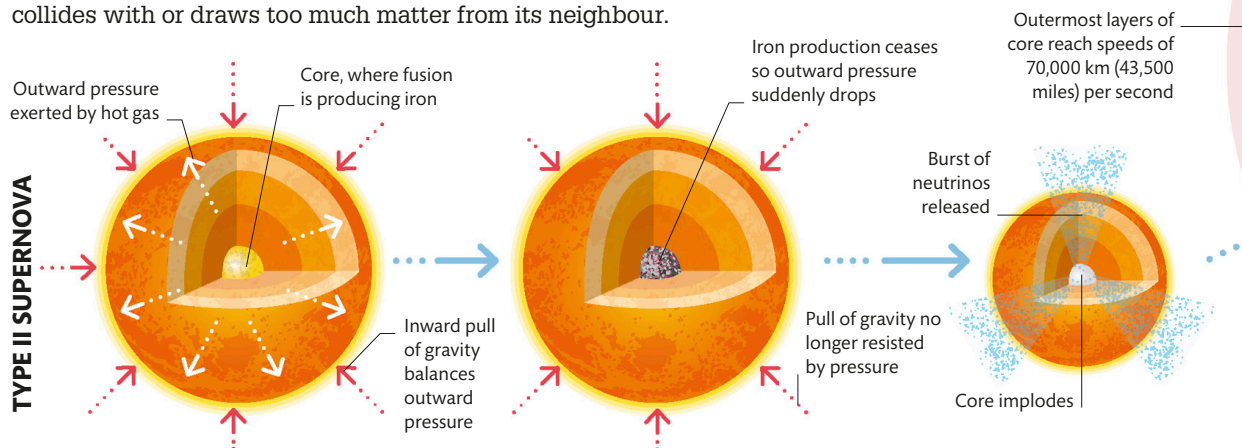
Stars can explode in spectacular phenomena called supernovae. The largest explosions humans have ever seen, supernovae can outshine galaxies for a few days and can even be seen across the Universe.

How stars explode

There are two main categories of supernova. A type II supernova is the natural end point for all high-mass stars that have run out of fuel. The star's core collapses in a quarter of a second, which triggers a colossal shockwave that causes an explosion. Type Ia supernovae happen in binary-star systems when a white dwarf star either collides with or draws too much matter from its neighbour.

WHAT WAS THE BRIGHTEST SUPERNOVA?

SN2016aps, recorded in 2016, may have been the most powerful supernova ever. It was a type II supernova triggered by the collapse of a giant star at least 40 times bigger than the Sun.



1 Red supergiant on the edge

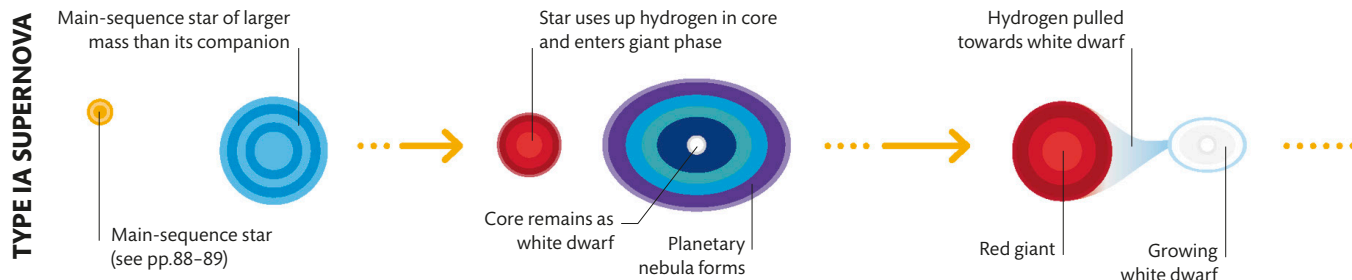
The star is supported by nuclear fusion taking place in its core and the shells around it. The core starts producing iron, but the fuel supply soon runs out.

2 Ready to collapse

When fusion into iron stops, the core collapses because there is not enough outward pressure from hot gas to counteract the inward force of gravity.

3 Core collapses

When the core collapses, it happens in seconds. This sets off a colossal shockwave that makes the outer part of the star explode.



1 Binary star system

Two stars orbit each other. One of the stars, being of greater mass, approaches the end of its life faster than its companion star.

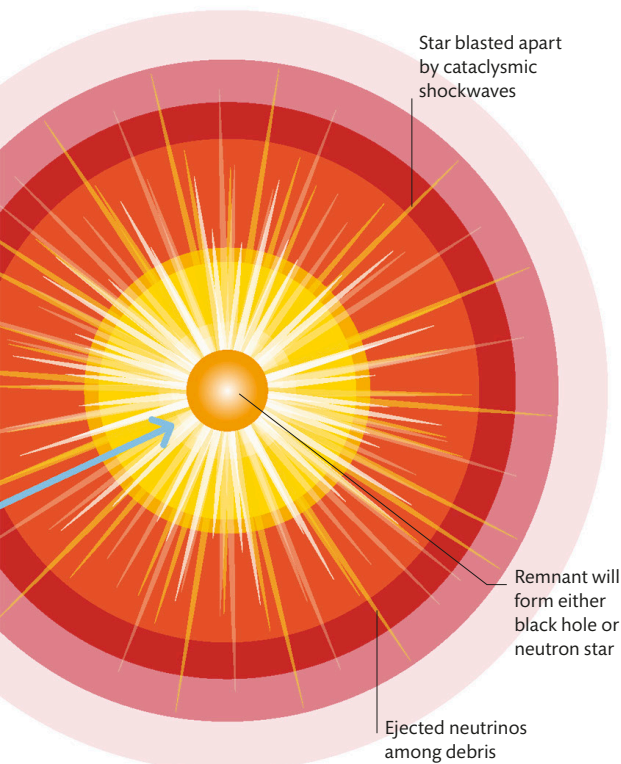
2 White dwarf forms

The higher-mass star blows off its outer layers, creating a planetary nebula, which exposes a white dwarf. The other star enters the giant phase of its life.

3 Gaining mass

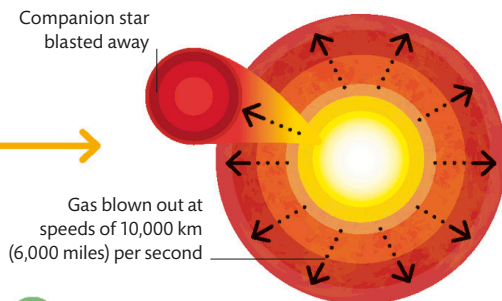
The two stars spiral in closer, and material from the swelling red giant spills onto the white dwarf, increasing its mass towards the maximum it can support.

THE LAST VISIBLE SUPERNOVA IN THE MILKY WAY WAS SEEN IN 1604



4 Star explodes

The explosion creates an expanding and incredibly bright cloud of hot gas, leaving behind a super-dense remnant core, which may become a black hole or a neutron star depending on the star's mass.



4 Nuclear blast

As more hydrogen accumulates on the white dwarf, it eventually heats up enough for fusion to begin suddenly and explosively. The white dwarf is blasted apart and the companion star is ejected away.

Supernovae and heavy elements

Stars are the Universe's chemical forges, creating all the different natural elements. In their cores, stars convert simple elements like hydrogen into heavier elements (see p.91). These include elements, such as carbon and nitrogen, which are needed for life, plus iron, which forms planetary cores. Some of the heavier elements, such as copper and zinc, are made by the force of a supernova, which also scatters them across space.

1 H HYDROGEN	2 He HELIUM	3 Li LITHIUM	4 Be BERYLLIUM	5 B BORON	6 C CARBON
7 N NITROGEN	8 O OXYGEN	9 F FLUORINE	10 Ne NEON	11 Na SODIUM	12 Mg MAGNESIUM
13 Al ALUMINIUM	14 Si SILICON	15 P PHOSPHORUS	16 S SULPHUR	17 Cl CHLORINE	18 Ar ARGON
19 K POTASSIUM	20 Ca CALCIUM	21 Sc SCANDIUM	22 Ti TITANIUM	23 V VANADIUM	24 Cr CHROMIUM
25 Mn MANGANESE	26 Fe IRON	27 Co COBALT	28 Ni NICKEL	29 Cu COPPER	30 Zn ZINC

Created by stars

This diagram shows the various origins of the 40 lightest elements. Hydrogen and helium formed soon after the Big Bang, but many of the elements were created either by exploding massive stars or by exploding white dwarfs.

KEY

- Big Bang
- Dying low-mass stars
- Cosmic ray fission
- Exploding massive stars
- Exploding white dwarfs

SUPERNOVA SPOTTING

Amateur astronomers can play a part in discovering supernovae by making their own observations of galaxies and by using their computers to examine images of galaxies. Supernovae are named by their year of discovery, prefixed by SN and followed by a letter code.



Pulsars

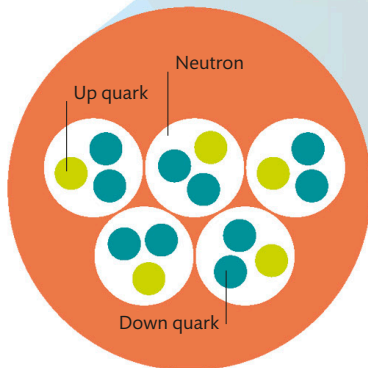
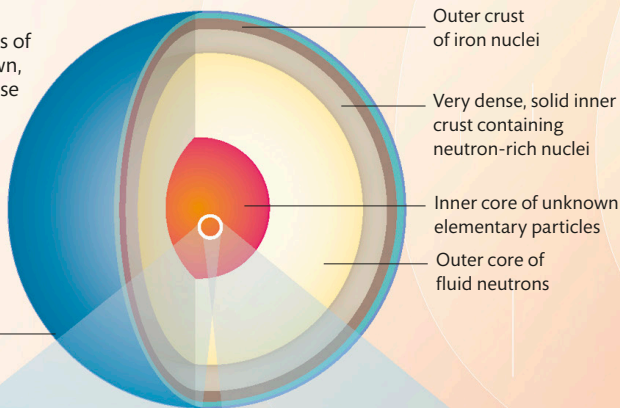
In the late 1960s, intense, regular radio pulses were detected from deep space. They came from neutron stars emitting powerful pulses as they spin. These stars became known as pulsars, an abbreviation for “pulsating radio star”.

Neutron stars

A neutron star is all that remains of a supergiant of over 10 solar masses after it has exploded in a supernova (see pp.118–19). The star collapses so powerfully under its own gravity that it is squeezed into a ball barely 20 km (12 miles) across. In a neutron star, protons and electrons are squeezed together to form a sea of tightly packed neutrons. Neutron stars are the densest objects in the Universe that can be observed directly.

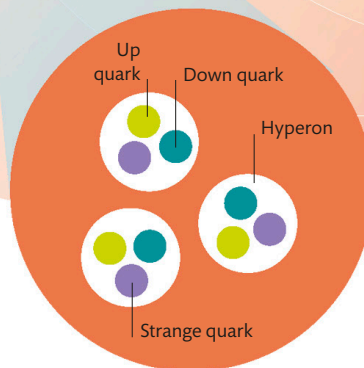
Inside a neutron star

While the outer features of a neutron star are known, the inner core is so dense that scientists have not determined what it comprises. There are several theories, including a traditional view and the hyperon core theory.



Traditional theory

This theory suggests that the inner core may consist of tightly packed neutrons containing three quarks – two “down” and one “up” quark.



Hyperon core theory

This theory indicates that under extreme pressure, a down quark could change into a “strange” quark, creating a subatomic particle called a hyperon.

HOW DO PULSARS SPIN SO FAST?

The fastest pulsars flash hundreds of pulses a second. These “millisecond” pulsars gain their speed from gases flowing from a companion star, which acts like a jet of water turning a wheel.

Neutron stars have hugely powerful magnetic fields, rotating at same speed as star

Star's powerful magnetic field accelerates particles out in a funnel along its two magnetic poles

Celestial lighthouse

Neutron stars that emit directed beams of radiation are known as pulsars. They are characterized by their strong magnetic fields and fast rotation. Over time their rotation speed slows down as they lose energy.



6 BILLION TONNES (13,000 BILLION LB) THE MASS OF A TEASPOON OF NEUTRON STAR MATERIAL

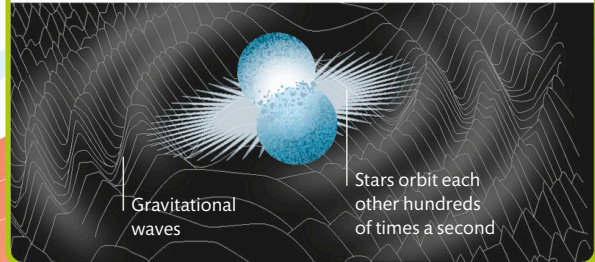
Speed of rotation comes
from rapid collapse of star

NEUTRON STAR

Neutron star's gravity is so strong that its solid surface, which is around a million times stronger than steel, is pulled into a smooth sphere

COSMIC COLLISION

Two neutron stars can orbit each other, like binary stars. If they move close enough, they may spiral to their own destruction. These collisions, called kilonovas, which emit bursts of gamma rays and may be the source of much of the Universe's gold, platinum, and other heavy elements. In 2017, gravitational waves reached Earth from a kilonova that occurred around 130 million years ago.

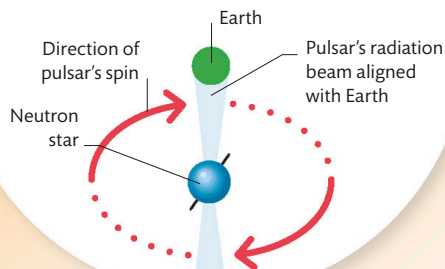


How a pulsar works

Most of the roughly 3,000 neutron stars that have been found are pulsars. Without the powerful beam of radio waves that pulsars emit, neutron stars are so tiny that they would otherwise be hard to see. Pulsars are like cosmic lighthouses, sending out pairs of radio beams that sweep across the Universe as they rotate, typically once every 0.25–2 seconds. Radio telescopes on Earth only spot pulsars at the moment that their beams sweep across Earth.

PULSAR "ON"

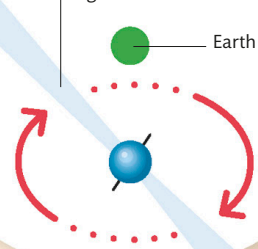
As a pulsar rotates, its two radiation beams continually sweep through space. At the instant shown here, one of the radiation beams points at Earth. This can be detected on Earth as a brief radio signal.



PULSAR "OFF"

At the moment shown here, neither of the radiation beams emanating from the pulsar points at Earth, so from the perspective of an observer on Earth, the pulsar is "off".

Radiation beam not aligned with Earth

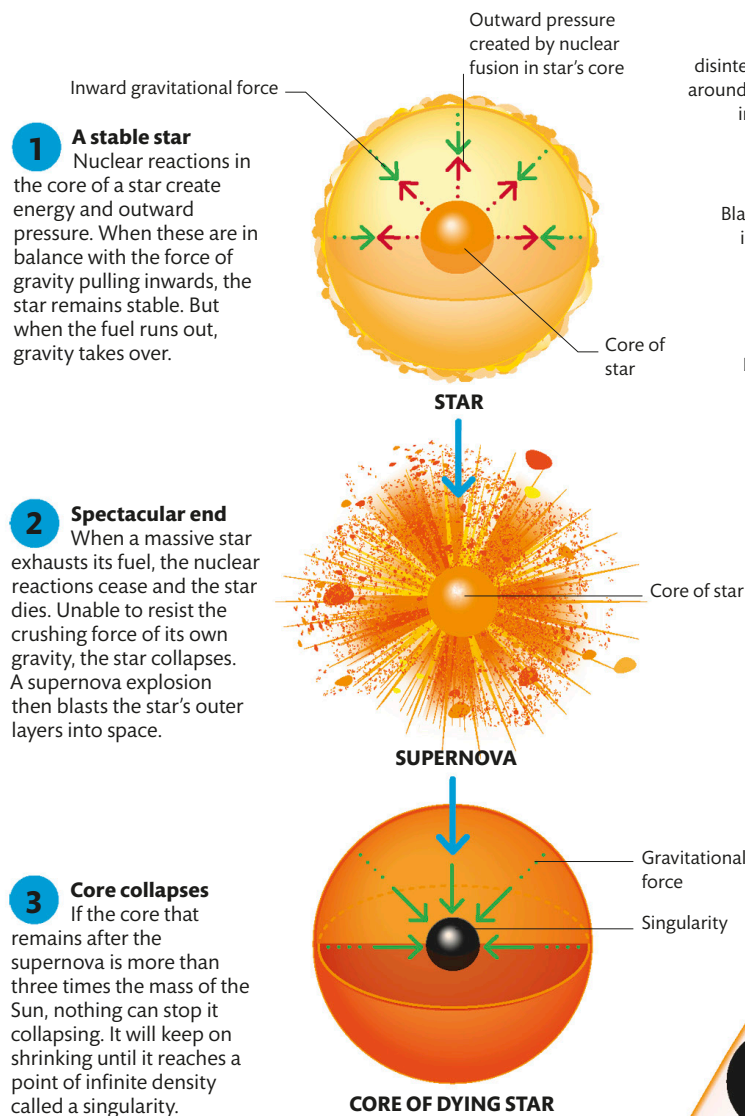


SUPERMASSIVE BLACK HOLES ARE THOUGHT TO LIE AT THE CENTRE OF MOST LARGE GALAXIES



How a black hole forms

Once a massive star has exploded in a supernova and its core collapses beyond a certain point, it becomes a stellar black hole. Matter that is pulled towards the black hole by gravity can form a spinning disc, releasing radiation that can be detected by astronomers. Supermassive black holes are thought to form after stars collide or through the merging of many smaller black holes.



Gas, dust, and disintegrated stars spiral around some black holes in what is called an accretion disc

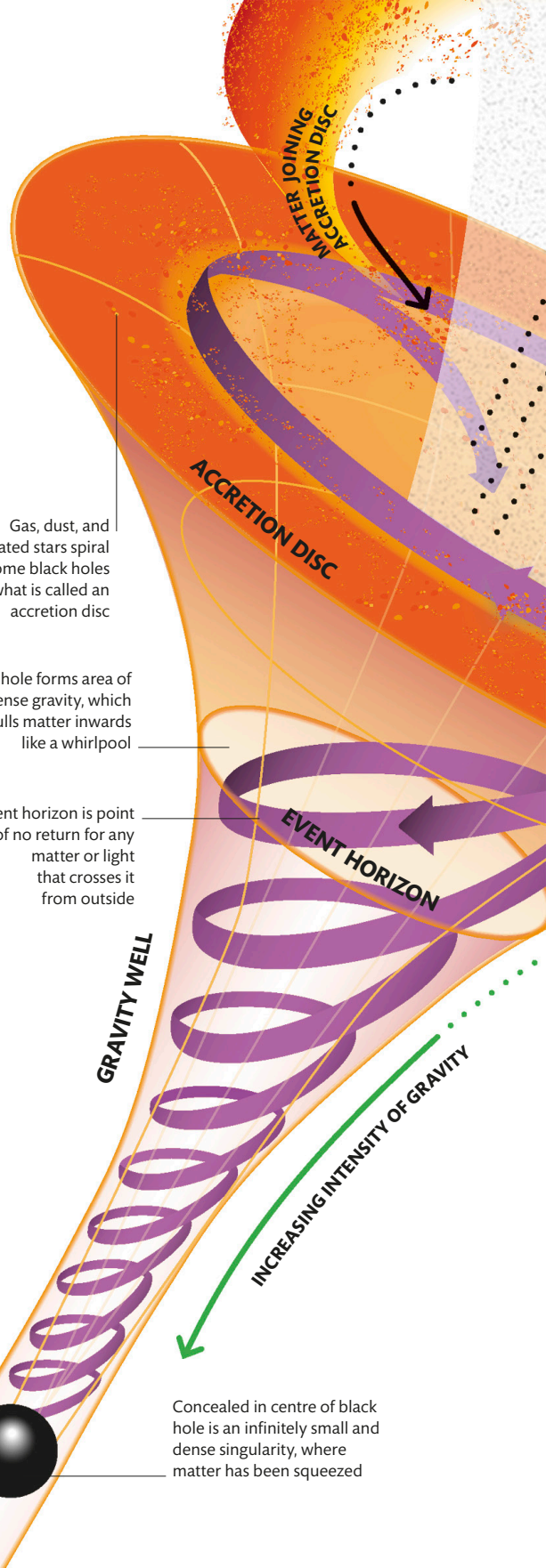
Black hole forms area of intense gravity, which pulls matter inwards like a whirlpool

Event horizon is point of no return for any matter or light that crosses it from outside

GRAVITY WELL

INCREASING INTENSITY OF GRAVITY

Concealed in centre of black hole is an infinitely small and dense singularity, where matter has been squeezed



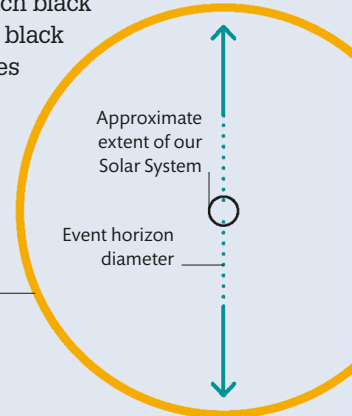


Black holes

Black holes are regions in space where gravity is so strong that it sucks everything in, including light. A black hole can form when the core of a massive star turns to iron and implodes under gravity.

Types of black hole

There are two main types of black hole: stellar and supermassive. Stellar black holes form when an old supergiant star collapses in a supernova. From the number of giant stars in the Milky Way, scientists estimate there could be up to a billion such black holes in this galaxy alone. Supermassive black holes are far larger than stellar black holes and are thought to have masses up to billions of times that of the Sun. There is also evidence for a third, mid-sized type that is intermediate in mass between stellar and supermassive black holes.



Diameter of event horizon of Holm 15a, the most massive black hole known

Contrasting sizes

While stellar black holes are relatively small, the Holm 15a supermassive black hole, discovered in 2019, is thought to be 40 billion times the mass of the Sun.



STELLAR

Event horizon diameter: 30–300 km (20–200 miles)
Mass: 5–100 Suns

SUPERMASSIVE

Event horizon diameter: thousands of light years
Mass: billions of Suns

MATTER SPIRALLING INWARDS

Black holes can eject giant jets of electrically charged particles formed from remnants of the matter they sucked in

4 A black hole forms

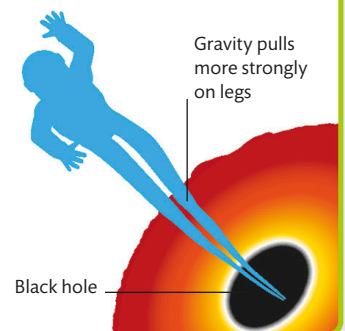
By now, the density of the singularity is so great that it distorts space-time surrounding it so that not even light can escape. A black hole can be pictured as an infinitely deep hole called a gravity well.

WHAT IS A WORMHOLE?

It is a theoretical tunnel through the curved fabric of space-time (see pp.154–55). Something could enter a wormhole at one point in space-time and emerge in another.

SPAGHETTIFICATION

Approaching a black hole's event horizon, the gravitational pull increases so significantly that objects dragged towards it are stretched into long, spaghetti-like strands. An astronaut would be torn apart, legs first, by this "spaghettification" process. Time would run at different speeds for his head and feet.





GALAXIES

AND THE

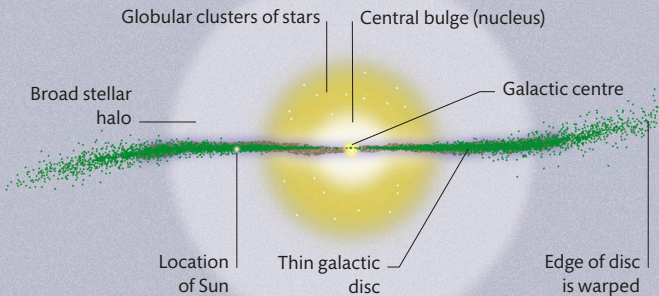
UNIVERSE

The Milky Way

Our galaxy, the Milky Way, is a medium-sized spiral galaxy. It is only one of the two trillion galaxies in the Universe – groups of stars, gas, and dust held together by gravitational attraction.

The structure of the Milky Way

The Milky Way is a typical spiral galaxy. It has an elongated bulge, or nucleus, at its centre, with a supermassive black hole at its very core (see pp.128–29). Two major spiral arms – the Scutum-Centaurus Arm and the Perseus Arm – extend from each end of the central bar, and there are also several minor arms. The arms form a thin disc 100,000–120,000 light-years across. There is also a spherical halo of stars about 170,000–200,000 light-years in diameter.



Side view of the Milky Way

Precise measurements of the positions of Cepheid variable stars (see p.98), shown in green, have shown that our galaxy is warped at its edges. This warping may have been the result of a past collision with another, smaller galaxy.

HOW MANY STARS ARE IN THE MILKY WAY?

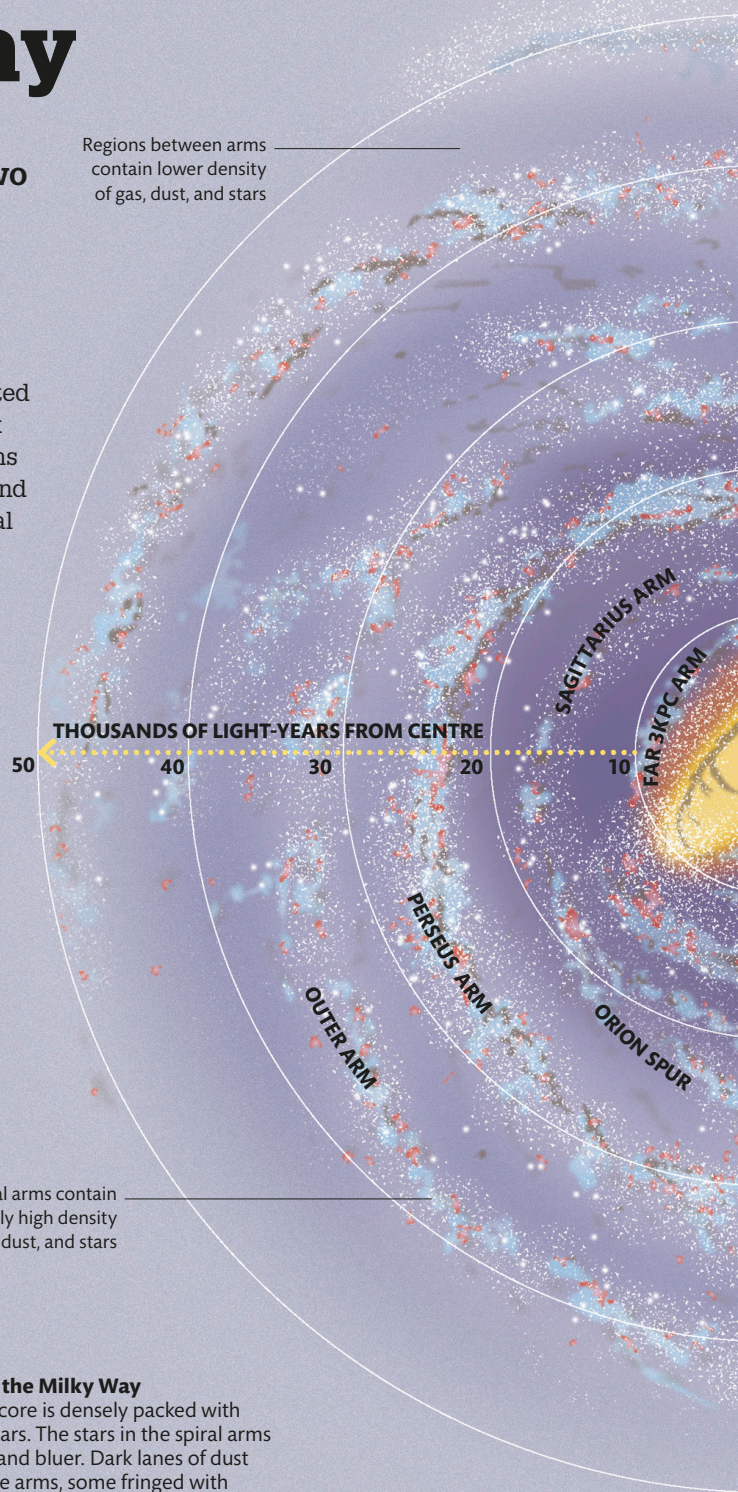
Most stars are too dim to be easily observed, but the Milky Way is thought to contain 100–400 billion stars.

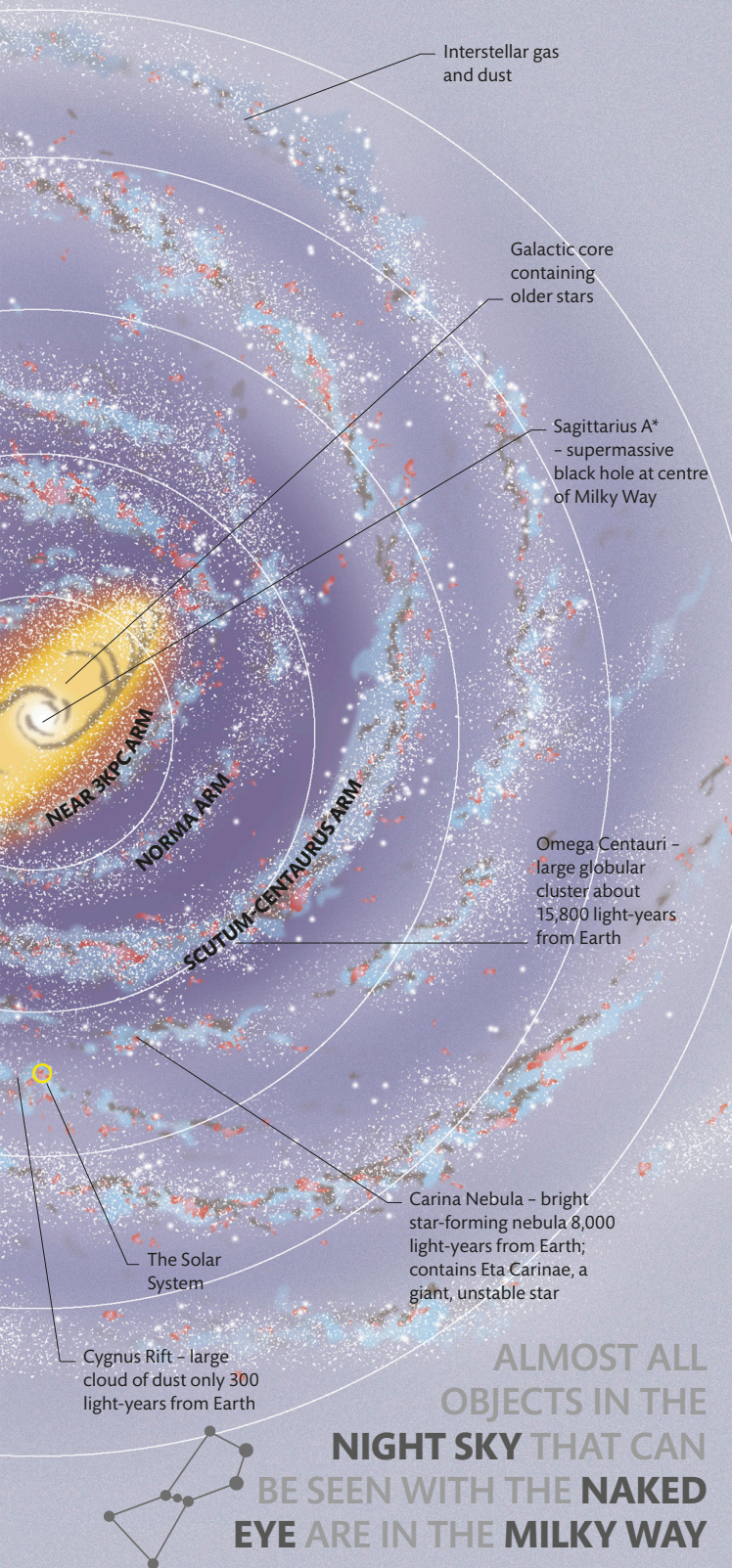
Anatomy of the Milky Way

Our galaxy's core is densely packed with old, yellow stars. The stars in the spiral arms are younger and bluer. Dark lanes of dust criss-cross the arms, some fringed with glowing red nebulae of ionized gas. The oldest stars are outside the disc in globular star clusters that form part of a broad, sparsely populated stellar halo.

Regions between arms contain lower density of gas, dust, and stars

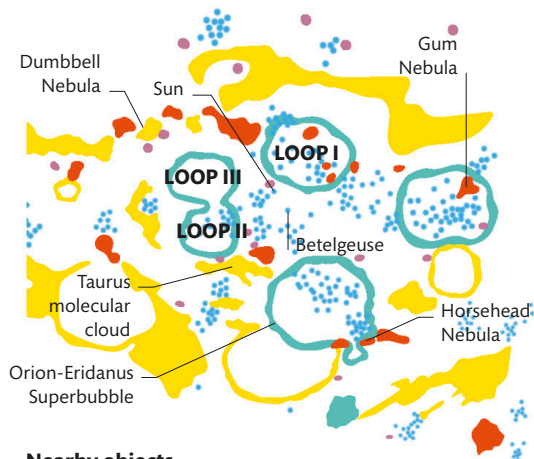
Spiral arms contain relatively high density of gas, dust, and stars





Our local neighbourhood

The Sun lies about 26,000 light-years from the galactic centre, on the edge of the Orion Spur. We are in a bubble of hot, ionized (electrically charged) hydrogen gas surrounded by clouds of cooler dust and molecular hydrogen gas (in which each hydrogen molecule is in the form of two linked atoms) alive with star-forming nebulae. Neighbouring bubbles are outlined by loops of glowing interstellar dust.

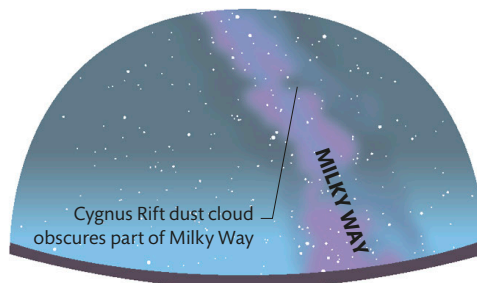


Nearby objects

This map of the Milky Way's local neighbourhood shows part of the Orion Arm. The Sun is towards the centre; hydrogen gas clouds are shown in yellow, gas and dust clouds in red, and star clusters and giant stars are blue.

THE MILKY WAY IN THE SKY

The Milky Way appears as a bright, whitish, hazy band, densely populated with stars, running across the night sky. When we look at the band, we are looking into the depths of our galaxy's disc.



MILKY WAY FROM THE NORTHERN HEMISPHERE

**ALMOST ALL
OBJECTS IN THE
NIGHT SKY THAT CAN
BE SEEN WITH THE NAKED
EYE ARE IN THE MILKY WAY**



The centre of the Milky Way

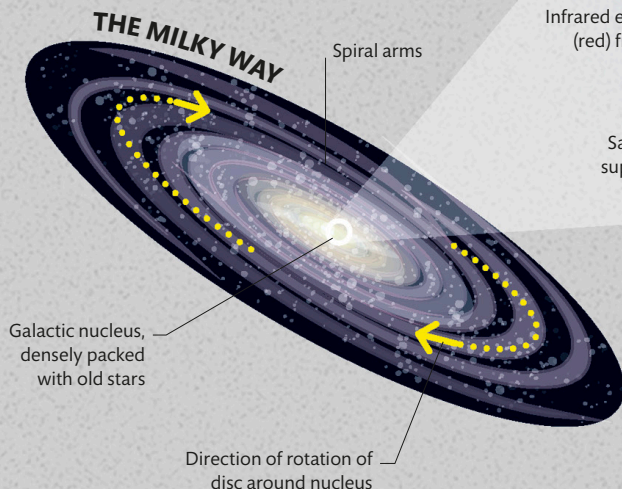
The nucleus of our galaxy takes the form of a central bulge that extends for about 800 light-years. Densely packed with stars, it contains the supermassive black hole Sagittarius A* at its centre.

The galactic centre

The nucleus of our galaxy is obscured at visible light wavelengths by dust. However, it can be studied using other wavelengths, such as infrared and radio waves, which can penetrate the dust. A strong source of radio waves known as Sagittarius A lies at the centre of our galaxy. It consists of Sagittarius A* (often abbreviated to Sgr A*), a supermassive black hole; Sagittarius A East, a supernova remnant; and Sagittarius A West, a collection of gas and dust falling into Sgr A*. Shorter-wavelength X-rays and gamma rays are emitted from the centre, indicating intense activity, with dust and gas being accelerated to extremely high speeds.

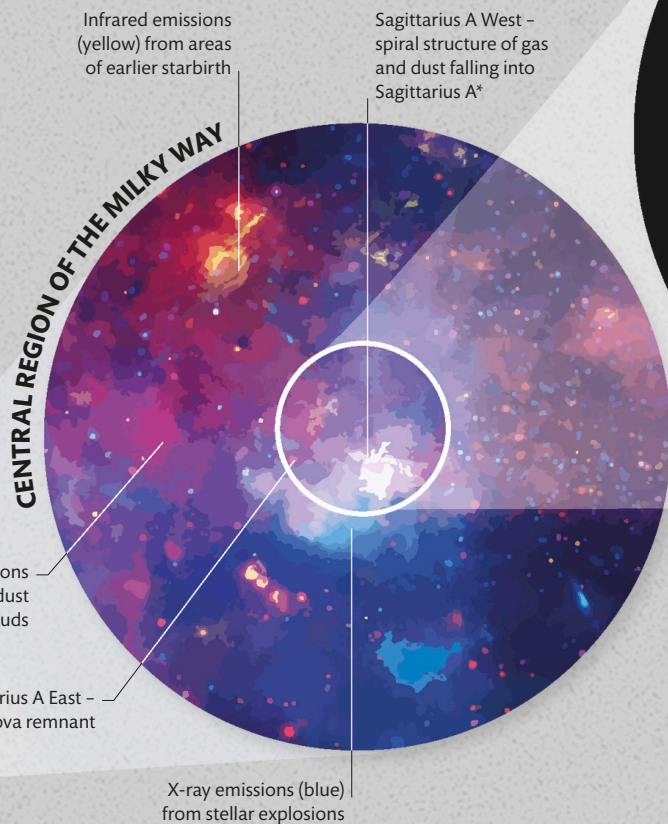
The Milky Way's hub

Most of the stars in the central region of our galaxy are old red giants, although there are also a few younger stars orbiting close to Sagittarius A*, which were possibly formed in the disc of gas there.



HOW DO WE KNOW WHERE THE CENTRE OF THE MILKY WAY IS?

All of the objects in the Milky Way appear to revolve around the supermassive black hole Sagittarius A*, so it must be the centre of our galaxy.

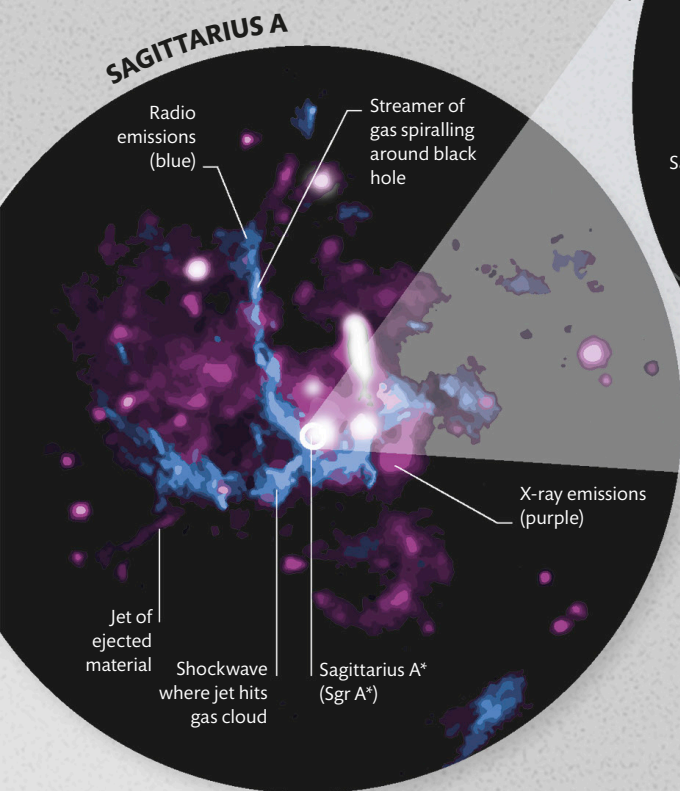


THE BLACK HOLE AT THE CENTRE OF THE MILKY WAY HAS A MASS EQUAL TO ABOUT 4.3 MILLION SUNS

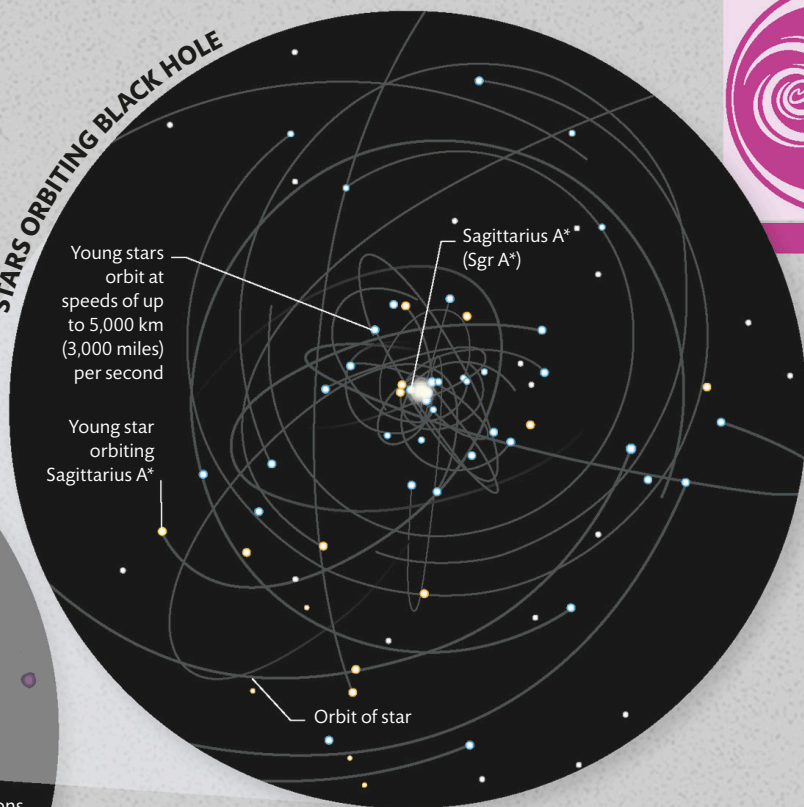


The heart of the Milky Way

At the very centre of our galaxy is an area of strong radio emissions, where material is being pulled in and torn apart by a supermassive black hole – Sagittarius A*. The black hole cannot be seen directly, but astronomers have confirmed its existence and measured its mass by tracking stars orbiting close to it.



STARS ORBITING BLACK HOLE



Supermassive black hole

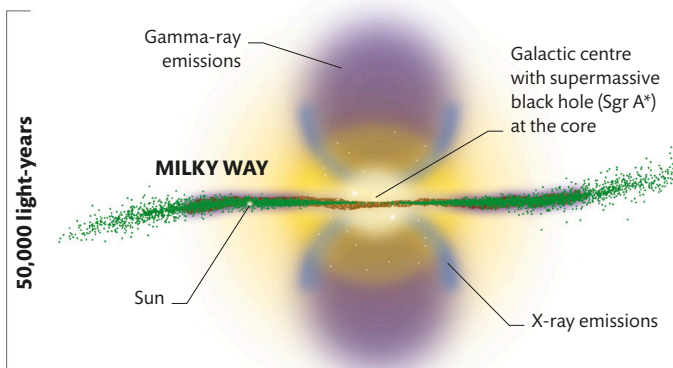
The Sagittarius A* radio source is about 44 million km (27 million miles) across, about 30 times larger than the Sun, yet the black hole at its centre has a mass around four million times the Sun's. Sagittarius A* is relatively dormant but emits intense X-ray megafares every few years, possibly caused by the breaking apart of objects such as asteroids falling into the black hole.

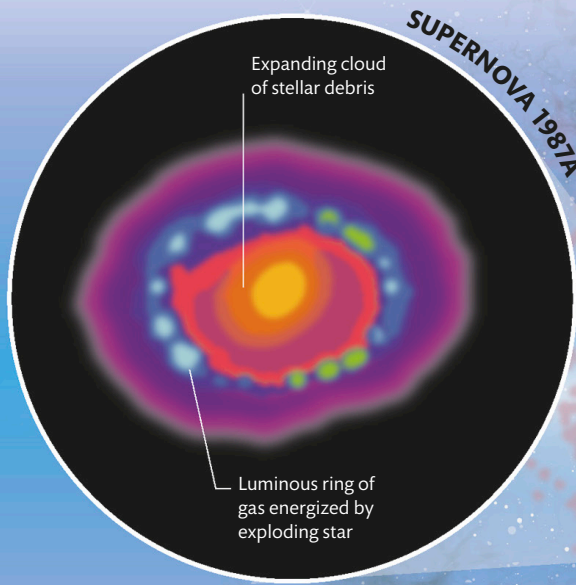
ACTIVITY AT THE CENTRE

Giant lobes of gas extend for thousands of light-years above and below the galactic centre, funnelled by streams of X-ray-emitting gas. These bubbles were discovered by the Fermi spacecraft, which detected the gamma rays also emitted by the gas. Gamma rays are the form of electromagnetic radiation that carry the most energy (see p.153).

Radiation emissions

The radiation emissions from the galactic centre are due to movement of material – possibly particle jets or gas from an earlier burst of star formation – away from the supermassive black hole Sgr A*.





SUPERNOVA 1987A

Stellar explosion

In 1987, a star in the LMC went supernova, blazing with the power of 100 million Suns, the brightest explosion seen from Earth in the last 400 years.

Large Magellanic Cloud

The Large Magellanic Cloud (LMC) is a dwarf spiral galaxy (see pp.140–41) with a prominent central bar and spiral arm. The gravitational pull of the Milky Way makes it a site of vigorous star formation. Like the Milky Way, the LMC contains globular and open star clusters, planetary nebulae, and clouds of gas and dust.

Leading arm of Magellanic Stream

Interaction between leading arm of Magellanic Stream and hot gas of Milky Way, leading to compression of gas and new star formation

MILKY WAY

**LARGE
MAGELLANIC
CLOUD**

**SMALL
MAGELLANIC
CLOUD**

Magellanic Bridge (blue) – cloud of hydrogen gas connecting the two Magellanic Clouds

Hydrogen gas from SMC pulled out by stronger gravity of LMC

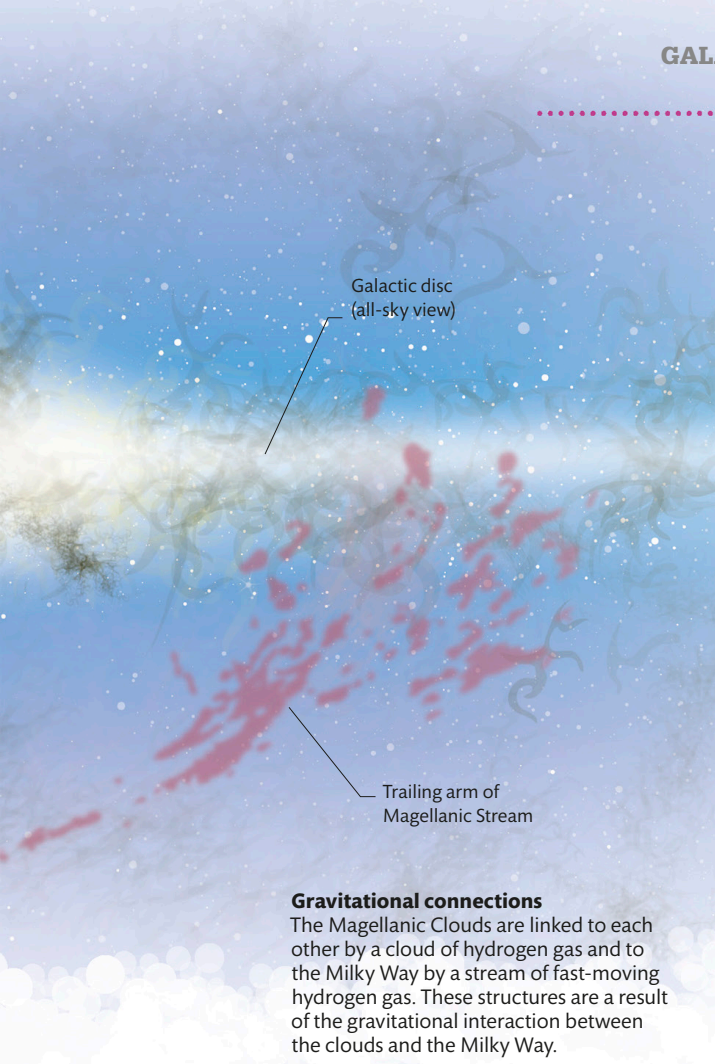
Magellanic Stream (red) – flow of high-velocity hydrogen gas linking Magellanic Clouds with Milky Way

The Magellanic Clouds

Named after Ferdinand Magellan, the Portuguese explorer who observed them as he sailed south of the equator in 1519, the Magellanic Clouds are a spectacular feature of the night sky in the southern hemisphere. Lying in the constellations Dorado and Tucana near the south celestial pole, these irregular clouds of stars are small galaxies in their own right and two of the Milky Way's closest neighbours.

WHO DISCOVERED THE MAGELLANIC CLOUDS?

The clouds have been known since ancient times by indigenous peoples of the southern hemisphere. The first written references to them are by Arab scholars in about the 9th century CE.

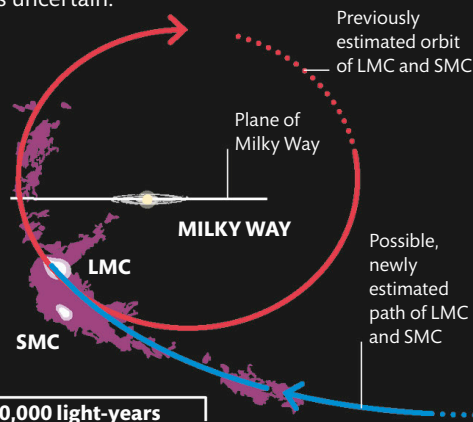


Gravitational connections

The Magellanic Clouds are linked to each other by a cloud of hydrogen gas and to the Milky Way by a stream of fast-moving hydrogen gas. These structures are a result of the gravitational interaction between the clouds and the Milky Way.

SATELLITES OR PASSERSBY?

The Magellanic Clouds are generally considered to be satellite galaxies orbiting the Milky Way. However, they may be independent bodies, just passing by. They seem to be moving too fast to be long-term satellites, but this interpretation depends on the mass of the Milky Way, which is uncertain.



**TO THE NAKED EYE, THE
MAGELLANIC CLOUDS
APPEAR AS FAINT, IRREGULAR
PATCHES IN THE SOUTHERN SKY**

Small Magellanic Cloud

An irregular dwarf galaxy, the Small Magellanic Cloud (SMC) is one of the most distant objects visible to the naked eye. It has the remnant of a central bar, which suggests that it may have been a barred spiral before it was disrupted by the gravitational influence of the Milky Way. There is also gravitational interaction between the two Magellanic Clouds: the SMC orbits around the LMC, and they share a common cloud of hydrogen gas – the Magellanic Bridge – that is a region of star formation.

THE MAGELLANIC CLOUDS COMPARED

The SMC is more distant, smaller, less massive, and has fewer stars than the LMC. Both are dwarf galaxies, but the SMC is an irregular galaxy whereas the LMC is a dwarf spiral.

	LMC	SMC
 DISTANCE FROM EARTH	163,000 light-years	200,000 light-years
 DIAMETER	14,000 light-years	7,000 light-years
 MASS	80 billion Suns	40 billion Suns
 NUMBER OF STARS	10–40 billion	Several hundred million

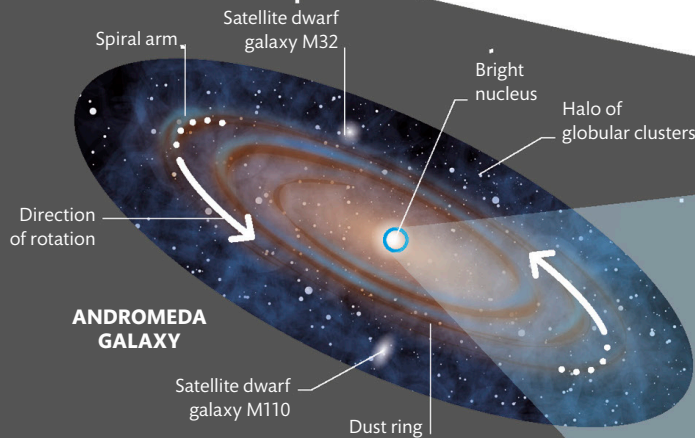
**WHEN WAS
THE ANDROMEDA
GALAXY DISCOVERED?**

The galaxy was first identified as a “nebulous smear” in the night sky by the Persian astronomer Al-Sufi in around 964 CE.

The Andromeda Galaxy

Andromeda is the closest large galaxy to the Milky Way and the brightest and largest of the Local Group (see pp.134–35). It is a barred spiral, like the Milky Way, and studying Andromeda has helped us understand the nature of our own galaxy.

**THE ANDROMEDA GALAXY IS ON
COURSE TO COLLIDE WITH THE MILKY
WAY IN ABOUT 5 BILLION YEARS**

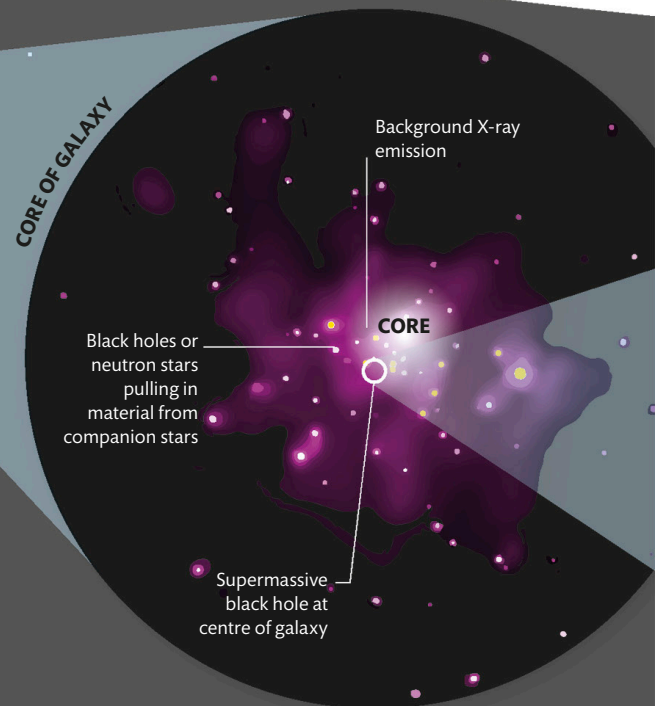


Andromeda's structure

Andromeda's bright centre is visible to the naked eye. The dim outer reaches of its disc extend seven times the diameter of the full Moon. It has at least 13 dwarf galaxy satellites.

Identifying the Andromeda Galaxy

For a long time, Andromeda was regarded as an astronomical cloud, or nebula. It was first recognized as a galaxy in its own right in 1925, when Edwin Hubble calculated the distance to its Cepheid variable stars (see pp.98–99) and proved that they lay outside the Milky Way. Located about 2.5 million light-years from Earth, Andromeda is visible to the naked eye, but it is difficult to make out its structure because it lies almost edge-on to our view. However, infrared observations have revealed that it is a barred spiral galaxy with at least one huge ring of dust.



Galactic core

X-ray observations of Andromeda reveal 26 stellar black holes (see p.123) or neutron stars in its central bulge. Their intense gravitational fields are pulling material in from companion stars in binary star systems, releasing high-energy radiation. A supermassive black hole lies at the very centre of the galaxy.



The structure of the galaxy

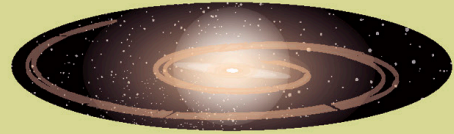
Distinct populations of stars can be seen in the Andromeda Galaxy: young blue stars in the spiral arms of the disc (and around the central black hole); and old red stars in the central bulge. The same pattern of star distribution is also found in our own galaxy. The Andromeda Galaxy has prominent, dark dust lanes, where most star formation is taking place, but these dust lanes are more circular than spiral in shape. A relatively small dust ring in the inner part of the galaxy may have resulted from an encounter with M32, a neighbouring dwarf galaxy in the Local Group, at least 200 million years ago.

COMPARING THE ANDROMEDA GALAXY AND THE MILKY WAY

Andromeda is twice the size and has twice the number of stars, but its overall mass might be the same or even lower compared with the Milky Way.

Andromeda Galaxy

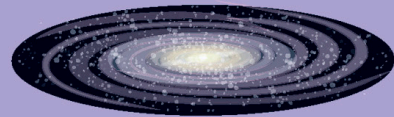
- **Galaxy type:** Barred spiral galaxy
- **Diameter:** 220,000 light-years (excluding halo)
- **Mass:** 1,000 billion Suns
- **Number of stars:** 1,000 billion
- **Number of globular clusters:** 460



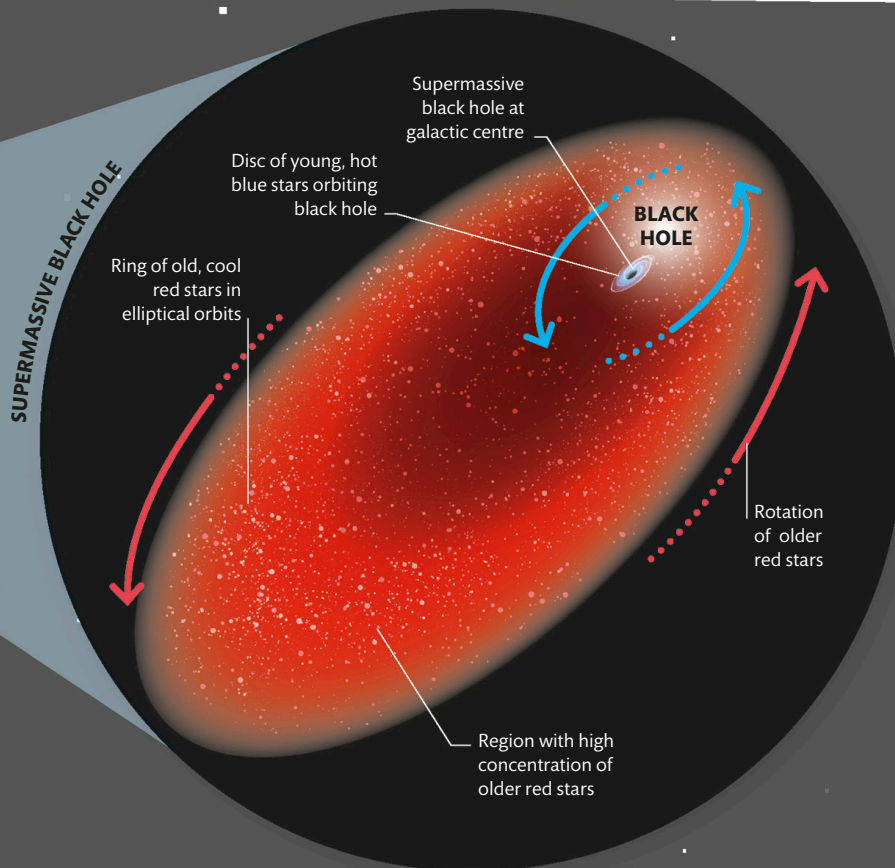
Andromeda's spiral arms are fragmented and may be transitioning to a more ringlike structure.

Milky Way

- **Galaxy type:** Barred spiral galaxy
- **Diameter:** 100,000–120,000 light-years (excluding halo)
- **Mass:** 850–1,500 billion Suns
- **Number of stars:** 100–400 billion
- **Number of globular clusters:** 150–158



The Milky Way has a well-defined spiral structure for both the stars and the dust lanes in its disc.



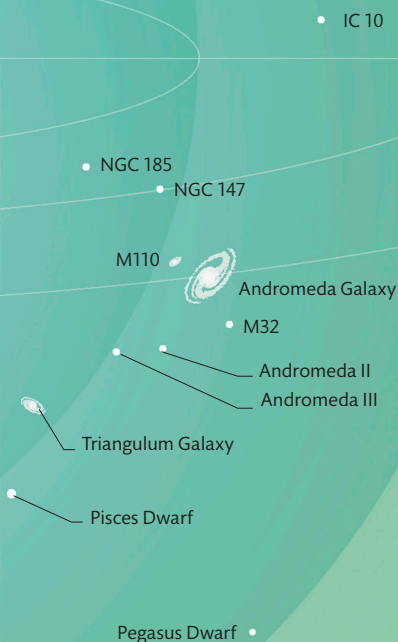
Supermassive black hole

Detailed images of the very centre of the Andromeda Galaxy show two bright areas. They correspond to a ring of older, cool red stars being pulled around in a wide ellipse, and a group of young, hot blue stars orbiting much closer to the central supermassive black hole.



The evolution of the Local Group

The Local Group is relatively young, so most of its gas is still contained within its galaxies, feeding star formation. The Milky Way's largest neighbours – the Magellanic Clouds (see pp.130–31) – are being pulled in by the gravity of their parent. Similarly, the Milky Way and Andromeda galaxies are moving closer together and will ultimately merge. The Local Group itself may one day merge with the nearest neighbouring galaxy cluster, the much larger Virgo Cluster (see pp.146–47).

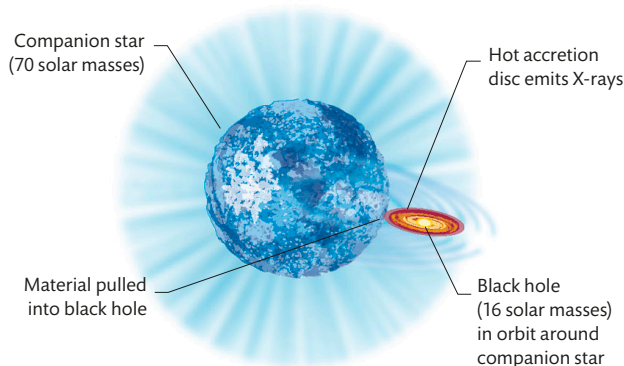


**THE ESTIMATED MASS
OF THE LOCAL GROUP
IS 2 TRILLION TIMES
THE MASS OF THE SUN**



The Triangulum Galaxy

Lying about 2.7 million light-years away, the Triangulum Galaxy is one of the most distant objects visible to the naked eye. It is the third largest member of the Local Group, with a diameter of about 60,000 light-years. Triangulum had a close encounter with the Andromeda Galaxy about 2–4 billion years ago, triggering star formation in Andromeda's disc.

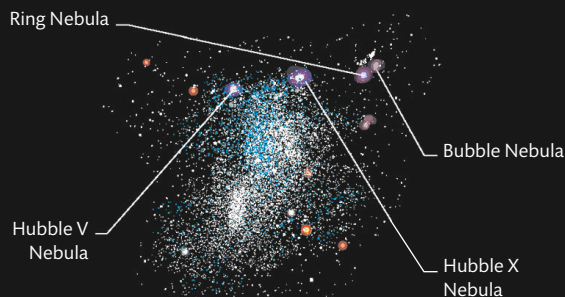


Stellar black hole

The Triangulum Galaxy contains an unusual binary star system, consisting of a black hole with about 16 times the mass of the Sun orbiting a much more massive star. X-rays are emitted as material from the star is pulled into the black hole.

BARNARD'S GALAXY

Barnard's Galaxy contains many areas of intense star formation, such as the Bubble, Ring, Hubble V, and Hubble X nebulae. Lying about 1.6 million light-years away, Barnard's Galaxy was one of the first systems outside our galaxy to have its distance calculated, from observations of its Cepheid variable stars (see pp.98–99).



Spiral galaxy structure

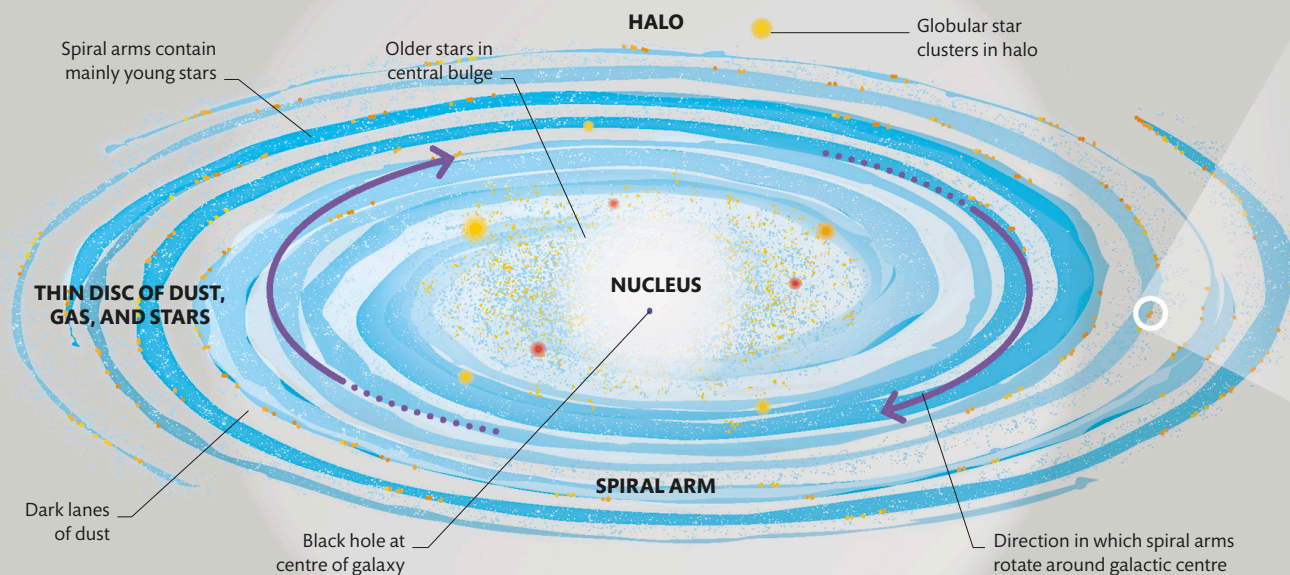
Spiral galaxies have a flattened disc rich in stars, gas, and dust. This material is concentrated into a number of arms that spiral around a central bulge, which is densely packed with stars and sometimes elongated into a bar. The spiral arms are bright with young blue stars, whereas older red and yellow stars dominate in the central bulge and in an extensive halo, which includes globular star clusters.



ABOUT TWO-THIRDS OF ALL OBSERVED GALAXIES ARE SPIRALS

Stars in spiral galaxies

In a typical spiral galaxy, most of the stars are situated in the flat galactic disc and in the spherical bulge of the nucleus around the central black hole. Some stars are also found in a broad, spherical halo, usually in compact globular star clusters.

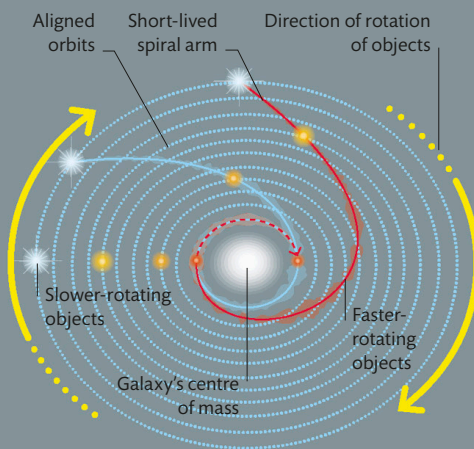


Spiral galaxies

Spiral galaxies are some of the most spectacular objects in the Universe. Their appearance depends on density variations within their discs, which determines the number of spiral arms, how tightly they are wound, and how distinct they are.

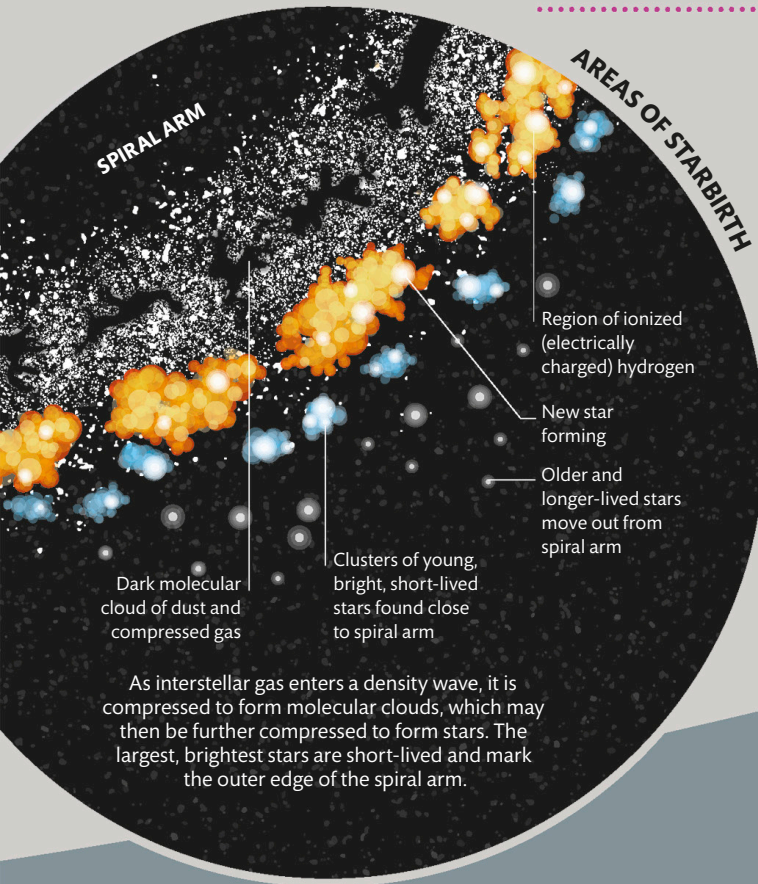
Spiral arms

A galaxy is not a solid structure but a fluid collection of stars, gas, dust, and other objects, all rotating about the galaxy's centre. Spiral arms originate as waves of high density in this material, which rotate more slowly than the material itself. Stars and gas enter a density wave in much the same way as cars enter a traffic jam, bunching up and moving through it and out to the other side. This bunching up triggers the creation of bright new stars that we see as the spiral arms.



Idealized galaxy

In an ideal galaxy, with objects moving at the same speed in aligned orbits, outer objects take longer to complete their orbits than those nearer the centre. Although spiral patterns develop, the spirals are soon so tightly wound that they become indistinct.

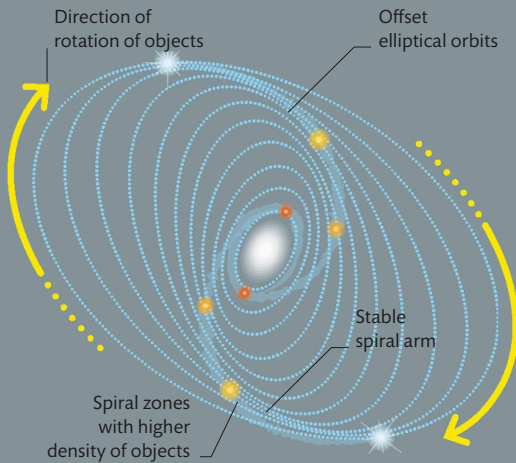


Activity in the spiral arms

The spiral arms are slow-moving density waves in the galactic disc, which give rise to areas of intense star formation as gas is compressed on entering the area of higher density. The brightest newborn stars emit lots of ultraviolet light, which ionizes hydrogen in the gas (splits hydrogen molecules into electrically charged particles) and causes it to glow. These bright stars and glowing gas are what give definition to the spiral arms.

WHICH IS THE LARGEST SPIRAL GALAXY?

In 2019, the Hubble Space Telescope imaged one of the largest known spiral galaxies, UGC 2885. Located about 232 million light-years away, it is about 2.5 times wider than the Milky Way and contains 10 times as many stars.

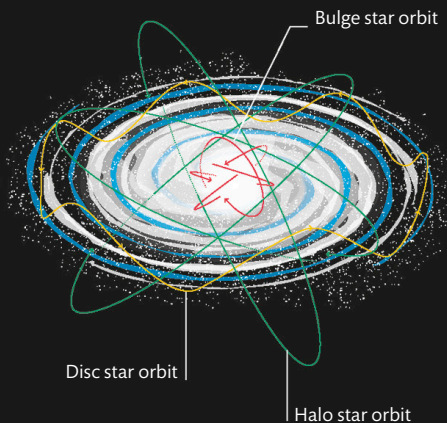


Real spiral galaxy

In a real galaxy, outer objects still take longer to complete their orbits than inner ones but their orbits are elliptical and are at slightly different angles. Over time, this leads to the objects bunching together in some places, producing the effect of stable spiral arms.

STAR ORBITS

Stars within the disc bob up and down while following elliptical orbits around the centre, roughly in the plane of the galaxy. Stars in the central bulge have short orbits at random angles, leading to a spherical distribution a few hundred light-years across. Similarly, stars in the halo orbit at all angles, but they plunge through the disc on long orbits that can take them thousands of light-years above and below the galactic plane.



Elliptical galaxies

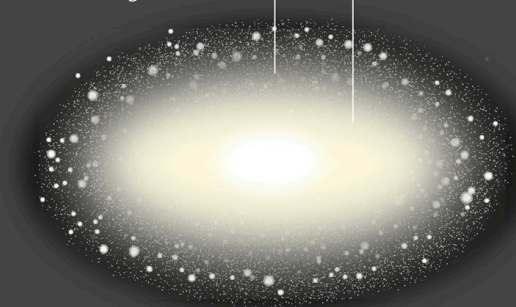
Elliptical galaxies are smooth balls of stars with little structure. They span a vast range of sizes, and their shape varies from oval to spherical. The biggest are far larger than any spiral galaxies. Lenticular galaxies share some features of ellipticals but also have certain similarities to spiral galaxies.

WHICH IS THE LARGEST KNOWN GALAXY?

The elliptical galaxy IC 1101 is the largest known galaxy of any type. It contains about 100 trillion stars, and has a halo up to 4 million light-years across.

Oval-shaped halo containing old yellow and red stars and many globular clusters

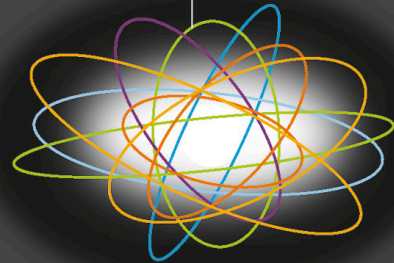
Galaxy contains little dust or gas



Anatomy of an elliptical galaxy

M86 is a typical elliptical galaxy, similar in size to the Milky Way but containing about 300 times as many globular clusters. It does not have a well-defined nucleus, and the star density decreases smoothly with distance from the centre.

Orbits tilted at any angle and with a large range of eccentricity



Orbits in elliptical galaxies

Elliptical galaxies have little interstellar dust and gas to interact with the stars and keep them flattened into a single plane, so the orbits of the stars are chaotic, inclined at any angle and varying in shape from circular to eccentric ellipses.

Elliptical galaxies

These galaxies vary enormously in size, from about a tenth the size of the Milky Way to supergiants tens of times wider than our galaxy. Ellipticals contain mostly older yellow and red stars with low mass. They have little interstellar gas or dust, and very little star formation occurs within them, probably because almost all of their gas and dust has already been turned into stars. A giant elliptical galaxy is often the central and brightest member of a galaxy cluster, but dwarf ellipticals are relatively dim and difficult to discover.

Giant elliptical galaxies

Ellipticals are some of the largest galaxies known. Compared with the Milky Way (a typical barred spiral galaxy), M87 is about 10 times wider; IC 1101, one of the largest galaxies currently known, is about 40 times wider. Both of these ellipticals contain many trillions of stars, compared to the hundreds of billions in the Milky Way.

MILKY WAY

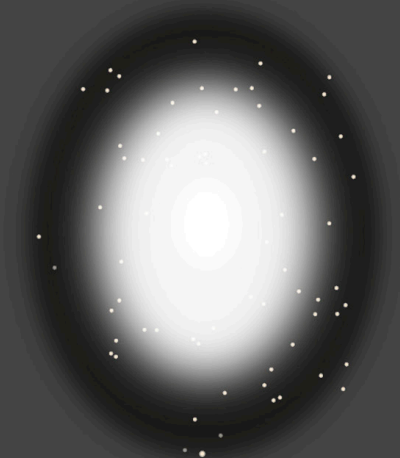
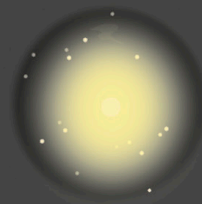
Barred spiral galaxy
170,000–200,000 light-years across; 100–400 billion stars

M87

Giant elliptical galaxy
1 million light-years across
Several trillion stars

IC 1101

Supergiant elliptical galaxy
4 million light-years across
About 100 trillion stars

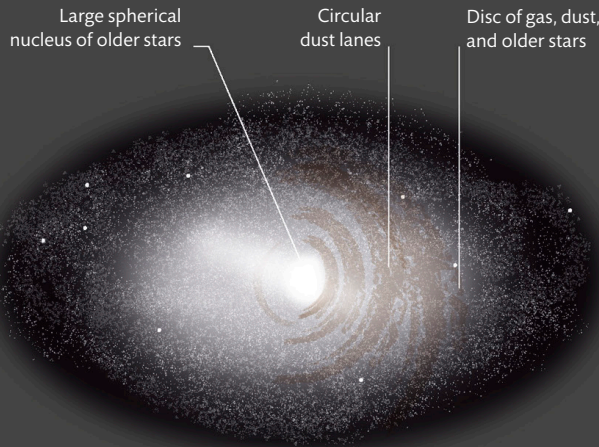
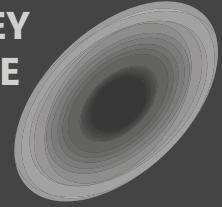




Lenticular galaxies

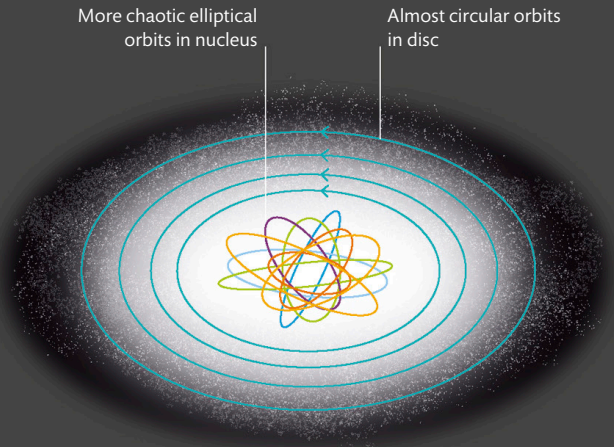
Lenticular galaxies have a similar appearance to ellipticals, especially when seen side-on, but, like spiral galaxies, they have a disc of gas and dust that flattens them into a lens shape – hence the name lenticular, which means lens-like. Some lenticulars may be spiral galaxies that have lost most, but not all, of their gas and dust. Like elliptical galaxies, lenticulars contain older stars and show little sign of new star formation.

DWARF ELLIPTICALS ARE DIM AND DIFFICULT TO OBSERVE, BUT THEY ARE PROBABLY THE MOST COMMON TYPE OF GALAXY



Anatomy of a lenticular galaxy

NGC 2787 is a lenticular galaxy that has a little more structure than most lenticulars, with concentric rings of dust in its disc. Like most lenticulars, NGC 2787 has a larger nucleus than a spiral galaxy of similar size.



Orbits in lenticular galaxies

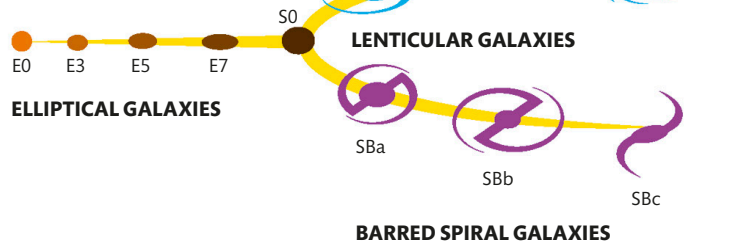
Stars typically follow well-ordered, almost circular paths in the disc of a lenticular galaxy. However, in the large central bulge, the stars' orbits are more varied and eccentric and are inclined at any angle.

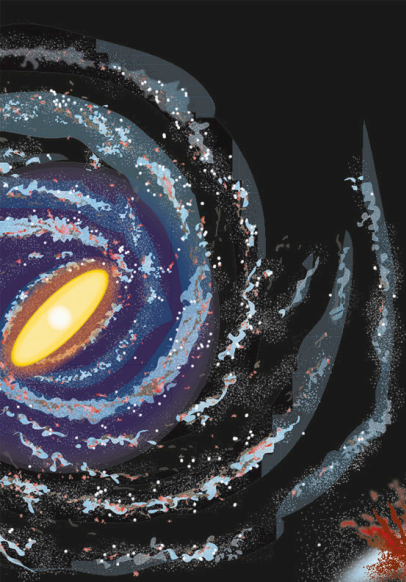
GALAXY CLASSIFICATION

Galaxies are commonly classified according to their shape, and a system still widely used today is the one devised by Edwin Hubble in 1926. He grouped galaxies into three main types according to their shape as seen from Earth: elliptical, lenticular, and spiral. These are commonly represented in a “tuning fork” diagram. The Hubble system is not intended to explain galaxy evolution, and we now recognize a fourth type: irregular galaxies, which do not have a distinct, regular shape (see p.141).

Hubble's galaxy classification

Ellipticals are numbered from E0 (circular) to E7 (highly elliptical). All lenticulars are classed as S0. Spirals are split into classic (S) and barred (SB) types.





Dwarf galaxies

Most of the approximately two trillion galaxies in the observable Universe are much smaller than the Milky Way. Some of these dwarf galaxies have definite shapes, such as spirals, but many are irregular.

Galaxy sizes

Dwarf galaxies are typically ten times smaller than the Milky Way and contain about a hundred-fold fewer stars (less than a few billion).

Milky Way
170,000–200,000
light-years across

Cigar Galaxy
40,000 light-
years across

NGC 4449
20,000 light-
years across

**Large Magellanic
Cloud**
14,000 light-
years across

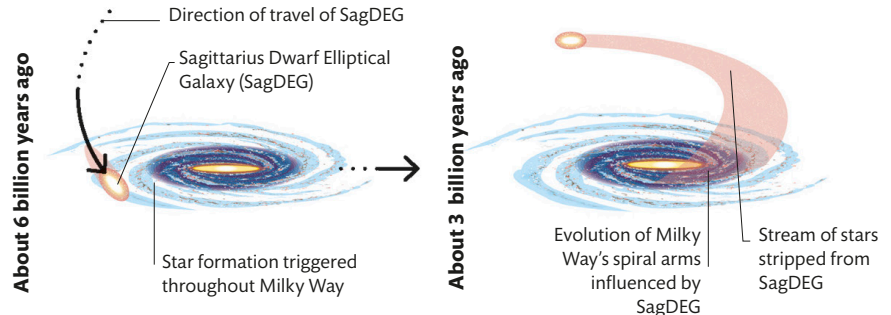
NGC 1569
8,000 light-
years across

**Small Magellanic
Cloud**
7,000 light-
years across

Zwicky 18
3,000 light-
years across

Features of dwarf galaxies

Most dwarf galaxies are held by the gravitational fields of larger galaxies, orbiting around them like planets around a star. However, some dwarf galaxies are moving independently of any larger body, and others are found in extreme isolation in the gaps between galaxy clusters. Dwarf galaxies are thought to have formed early in the life of the Universe, producing some of the very first stars, before merging with neighbours to form larger galaxies (see pp.168–69). There are about 60 dwarf galaxies near the Milky Way; the biggest are the Large and Small Magellanic Clouds (see pp.130–31).



FIRST PASS THROUGH MILKY WAY

SETTLES INTO ORBIT AROUND MILKY WAY

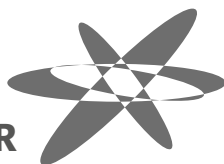
Sagittarius Dwarf interaction

The Sagittarius Dwarf Elliptical Galaxy has crashed through the Milky Way's disc at least three times, triggering star formation each time and slightly warping the disc of the Milky Way. The Sun was formed at about the time of the first encounter.

WHAT IS OUR NEAREST NEIGHBOURING GALAXY?

The Canis Major Dwarf Galaxy is only 25,000 light-years away, so it is closer to us than we are to the centre of our galaxy.

ABOUT A QUARTER OF ALL
KNOWN GALAXIES ARE
THOUGHT TO BE IRREGULAR



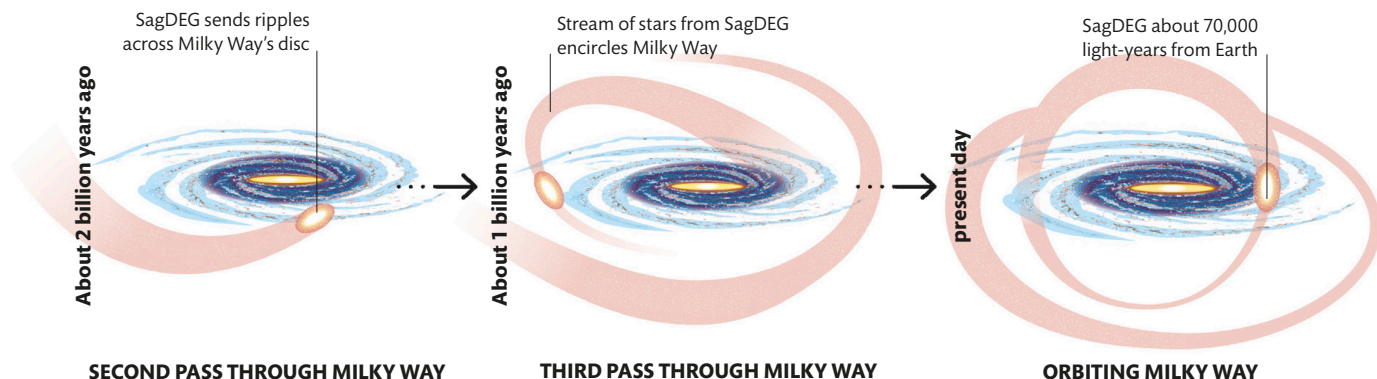
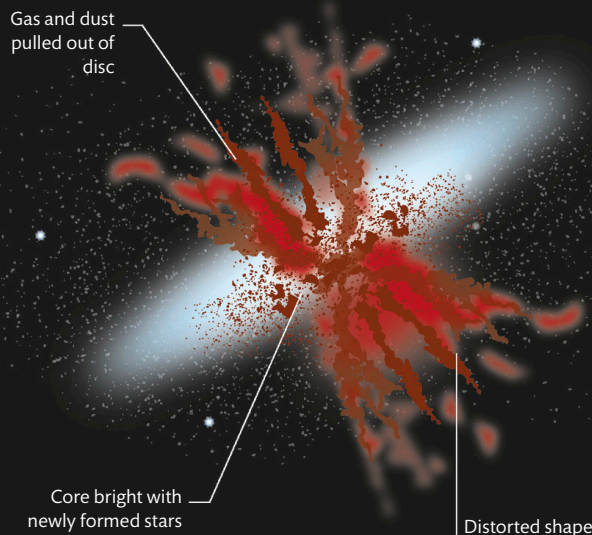


Irregular galaxies

Many dwarf galaxies are classified as irregular, although infrared observations have revealed that some, such as the Magellanic Clouds, have spiral or barred spiral structures. Because their mass is small, dwarf galaxies are easily pulled around and apart by the more powerful gravitational fields of larger, more massive neighbours, disrupting their original structures. Full-size galaxies can also be irregular. Many of these larger irregular galaxies show evidence of collisions with other galaxies, with distorted remnants of spiral structures, or bright areas of star formation – starbursts.

Starburst galaxy

An irregular starburst galaxy, the Cigar Galaxy is being distorted by the gravity of its larger neighbour, M81 (not visible in this image), triggering a high rate of star formation in its core.



TYPES OF DWARF GALAXY

Dwarf galaxies are classified according to their shape, features, and composition. As well as the spiral, elliptical,

and irregular types found in full-size galaxies, dwarf galaxies also include several unique types, such as compact dwarfs.



Dwarf elliptical galaxies

Smaller and fainter than ordinary ellipticals; possibly remnants of low-mass spirals or young galaxies



Dwarf spiral galaxies

Dwarf spirals are relatively rare; most are located outside galaxy clusters, far from gravitational interactions



Dwarf spheroidal galaxies

Small, low-luminosity galaxies similar to globular clusters but differentiated from them by having more dark matter



Compact dwarf galaxies

Blue compact dwarfs contain young, hot, massive stars; ultra-compact dwarfs are even smaller and tightly packed with stars



Dwarf irregular galaxies

Small galaxies with no distinct shape; thought to be similar to the earliest galaxies formed in the Universe

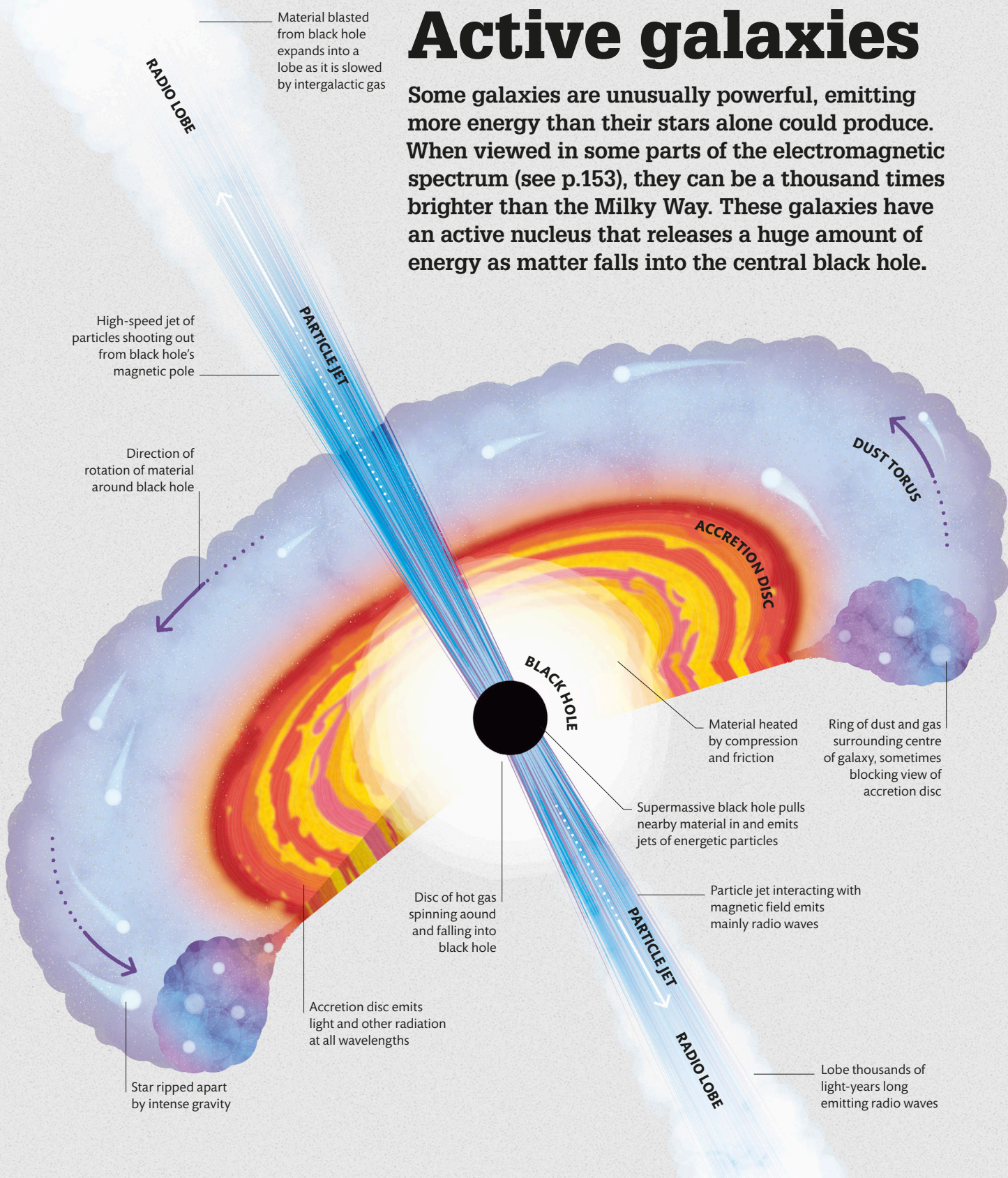


Magellanic spiral galaxies

Dwarf galaxies with only one spiral arm, like the Large Magellanic Cloud; intermediate between dwarf spiral and irregular galaxies

Active galaxies

Some galaxies are unusually powerful, emitting more energy than their stars alone could produce. When viewed in some parts of the electromagnetic spectrum (see p.153), they can be a thousand times brighter than the Milky Way. These galaxies have an active nucleus that releases a huge amount of energy as matter falls into the central black hole.





IS THE MILKY WAY ACTIVE?

Currently, our galaxy is dormant but the presence of lobes of gamma rays above and below the galactic disc indicates that it may have been active a few million years ago.

Extreme energy

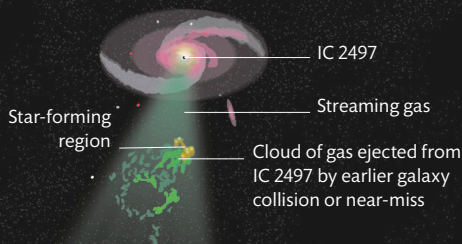
In active galaxies, the central supermassive black hole is consuming nearby matter, which forms a swirling disc that is compressed and heated as it is pulled in and torn apart. Up to a third of the mass pulled into the black hole is turned into energy, making active galaxies the most powerful long-lived objects in the sky. Most active galaxies are very distant from our galaxy, although a few are nearby, and all galaxies have the potential to become active.

Anatomy of an active galaxy

An accretion disc of heated material and a ring (torus) of dust surround the central black hole. Some active galaxies also have huge lobes of radio wave emissions, fed by jets of charged particles from the black hole's magnetic field.

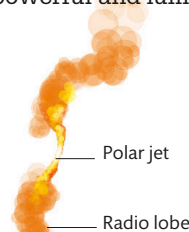
HANNY'S VOORWERP

Hanny's Voorwerp is an unusual object discovered in 2007. Glowing with ionized (electrically charged) oxygen, it was lit up by radiation from a quasar in nearby galaxy IC 2497. The quasar is no longer active but gas is still streaming from the galaxy, triggering star formation in the ionized cloud.



Types of active galaxy

Radio galaxies, Seyfert galaxies, quasars, and blazars are all types of active galaxy emitting X-rays and other forms of high-energy radiation. The type depends on the energy of the activity in the galaxy's nucleus, the mass of the galaxy, and its orientation to Earth. Seyfert galaxies and quasars (quasi-stellar objects) have similar orientations, but Seyferts emit far less energy than quasars, which are among the most powerful and luminous celestial objects known.

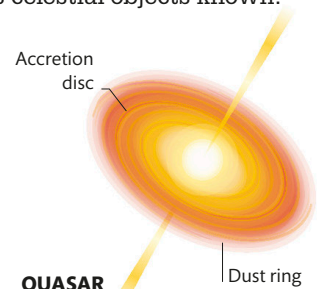


RADIO GALAXY NGC 383



Radio galaxy

In a radio galaxy, the central region of the nucleus is hidden by the edge-on dust ring, and observers on Earth see only the polar jets and radio lobes.

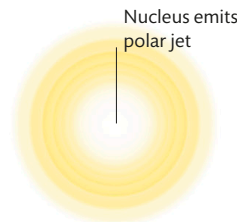


QUASAR PG 0052+251



Quasar

In quasars, the dust ring is tilted towards Earth, allowing us to see the brilliant light of the accretion disc, which outshines the light of the surrounding galaxy.

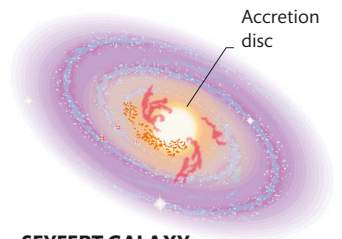


BLAZAR MAKARIAN 421



Blazar

A blazar is aligned so that observers on Earth look straight down the polar jet into the nucleus. The galaxy is hidden by the brilliant light, but the radio lobes can sometimes be detected.



SEYFERT GALAXY M106



Seyfert galaxy

A Seyfert galaxy has the accretion disc exposed to our view, as it is in a quasar, but the activity in the nucleus is weaker, which allows us to see the surrounding galaxy more clearly.



LIGHT FROM THE MOST DISTANT QUASARS HAS TAKEN MORE THAN 12 BILLION YEARS TO REACH US

Galaxy collisions

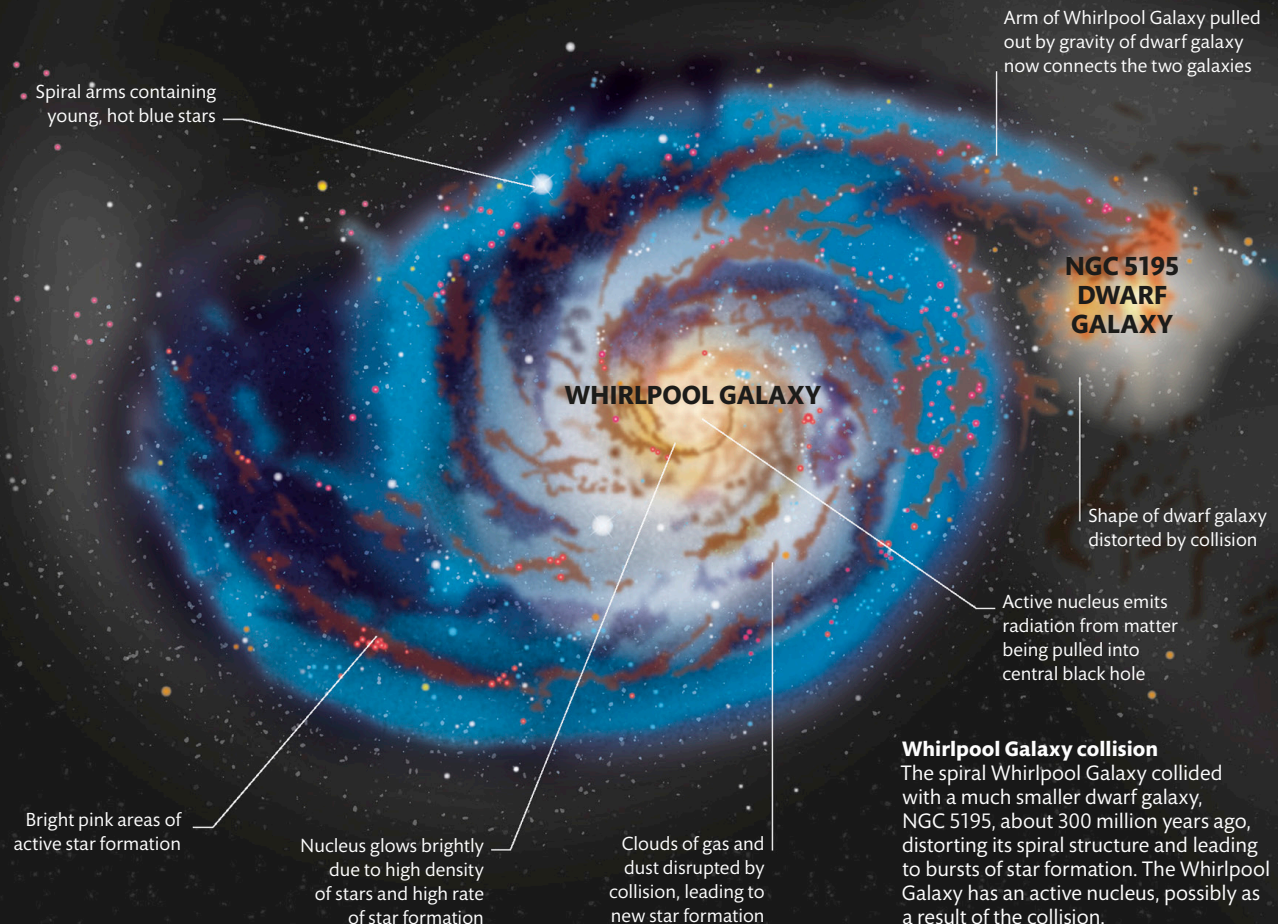
Packed together in clusters, galaxies are large relative to the distances between them, so close encounters and even collisions are common. Collisions can stimulate new star formation and also play a key role in galaxy evolution.

Galaxy interactions

When two galaxies come close, the outcome depends on how large they are and how close they approach. Their interaction may be minor, leading to slight distortion of their shapes, but a major interaction or collision can have dramatic effects, leading to bursts of new star formation or even tearing one or both galaxies apart. A collision can pull material out of a galaxy. It may also propel it into the central black hole, creating an active nucleus (see pp.142–43).

WHAT HAPPENS TO PLANETS WHEN GALAXIES COLLIDE?

When galaxies collide, the gravitational disruption may shift some planets in their orbits or even throw them out into interstellar space, but a collision between planets is very unlikely.



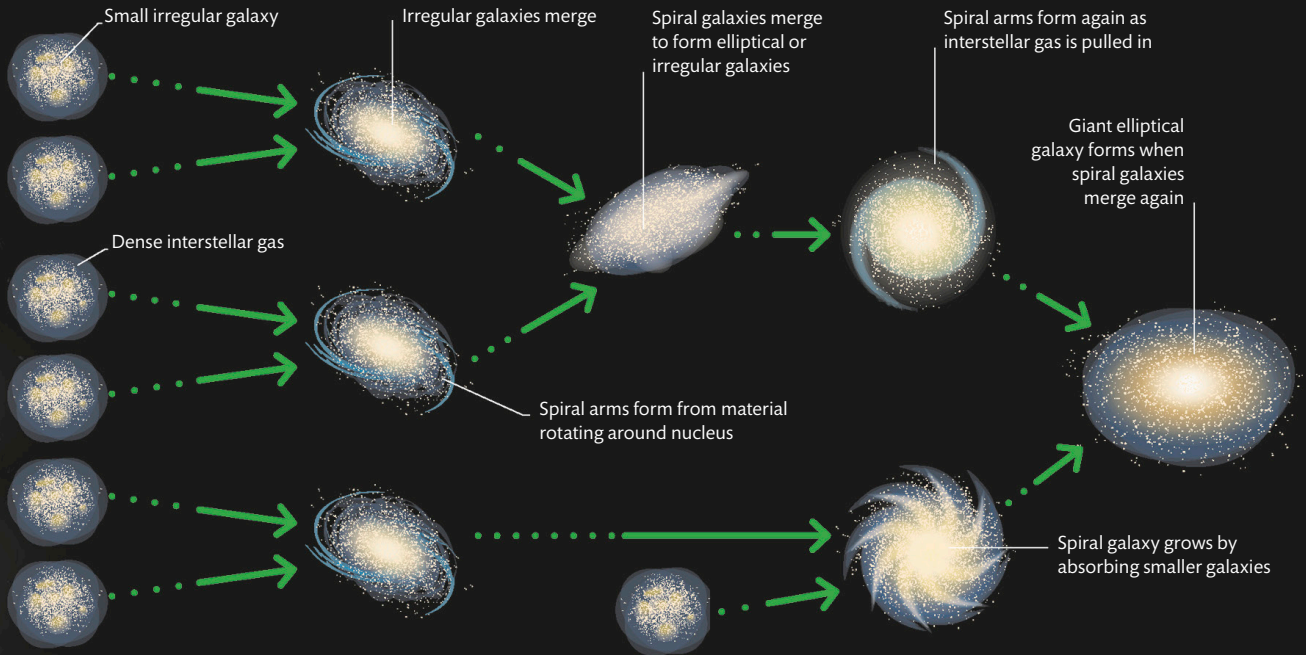


Galaxy evolution

Collisions are key to the transformation of one type of galaxy to another. Colliding galaxies may distort each other beyond recognition, or the larger one may engulf the smaller one. A spiral galaxy may be stripped of all its gas and dust, ending star formation and transforming it into an elliptical. Multiple collisions produce giant ellipticals, with their stars orbiting at random angles and any structure of their original constituents lost.

The merger model

According to one theory of galaxy evolution, galaxies undergo a series of mergers and collisions as their interstellar gas is consumed by star formation. The mergers form giant elliptical galaxies that eventually dominate the central areas of galaxy clusters.

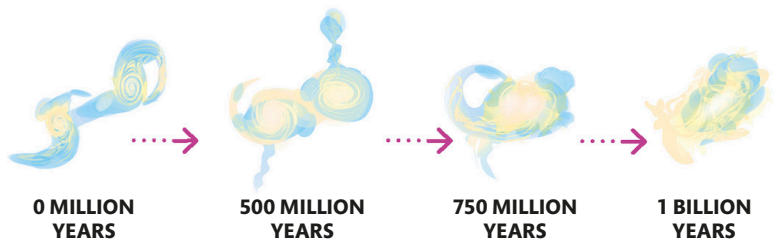


THE MERGER OF TWO LARGE GALAXIES CAN GENERATE NEW STARS TOTALLING THOUSANDS OF TIMES THE SUN'S MASS EVERY YEAR



SIMULATING GALAXY COLLISIONS

Collisions between galaxies happen over millions of years so it is impossible to observe the whole process. However, computer models using simplified, virtual galaxies can be used to simulate a collision to see what the fate of the galaxies might be. Here, a simulation shows how the structure of two galaxies is disrupted as they collide and merge over a period of a billion years.



Galaxy clusters and superclusters

Although some galaxies exist in isolation, most are found in crowds. Their immense gravity pulls them together into small groups, large clusters, and even larger superclusters, some of the largest structures in the Universe.

Superclusters

Galaxy clusters (see below) are themselves grouped into superclusters. Superclusters lie along filaments and sheets between largely empty voids in space (see pp.150–51). There are millions of superclusters in the Universe. The variations that have been detected in the cosmic microwave background radiation (see pp.164–65) – the “echo” of the Big Bang – suggest that these large-scale concentrations of matter date from very early in the life of the Universe. Tiny differences in temperature and matter density during this time gave rise to the first dwarf galaxies, which interacted with their neighbours to grow into galaxy groups, clusters, and superclusters.

Laniakea Supercluster

Our local supercluster, to which the Milky Way and the Local Group belong, is the Laniakea Supercluster. Several nearby superclusters, including the Virgo Supercluster, are now considered to be part of this larger structure.

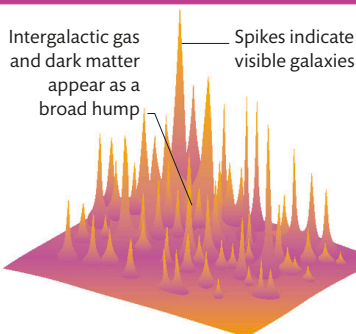
HOW BIG IS THE LARGEST SUPERCLUSTER?

The Caelum Supercluster, the largest detected, is about 910 million light-years across and contains about half a million galaxies.

 **50–1,000**
THE NUMBER OF GALAXIES IN
A TYPICAL GALAXY CLUSTER

THE MISSING MASS

The mass of the stars in a cluster's galaxies does not provide enough gravitational attraction to hold the cluster together. Intergalactic gas provides much more of a cluster's mass, and even more exists as dark matter. Gravitational lensing (see pp.148–49) can help to map a cluster's dark matter, which is distributed more broadly than the visible matter we see as galaxies.



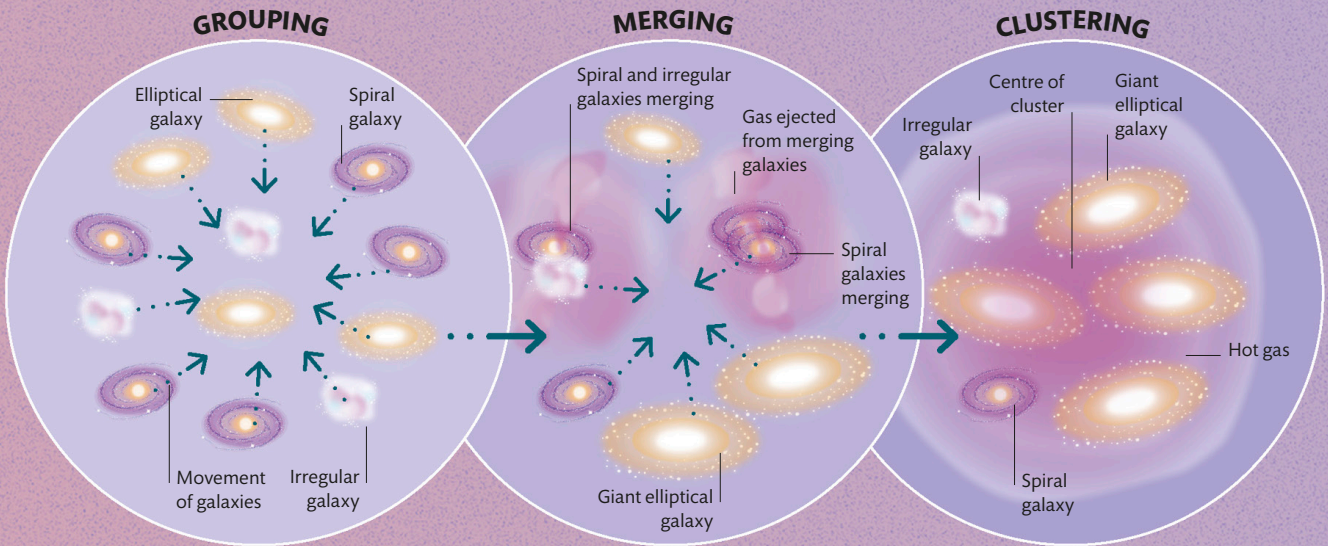
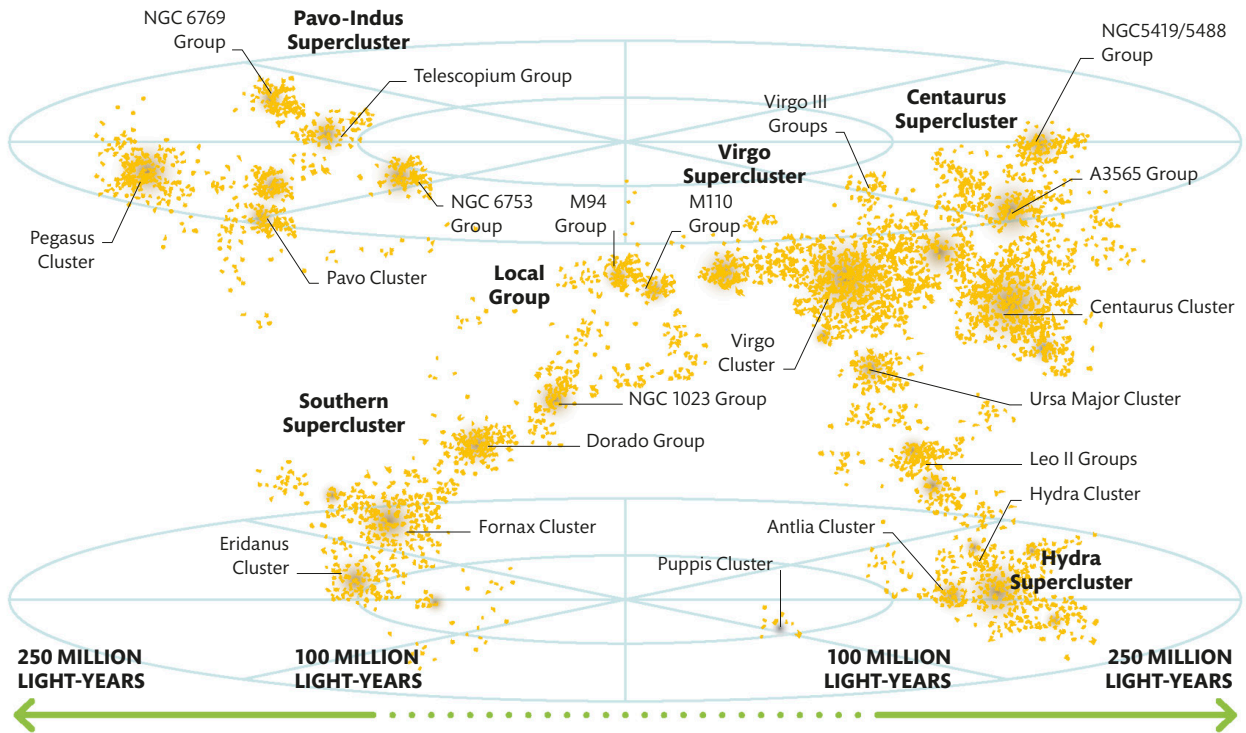
MASS DISTRIBUTION IN A GALAXY CLUSTER

Groups and clusters

Clusters may be relatively sparse, like our Local Group (see pp.134–35), or more densely packed, like the nearby Virgo Cluster. But regardless of how many galaxies they contain, clusters all tend to occupy a similar volume of space, a few million light-years across. The most populous clusters have a dense, spherical distribution of giant elliptical galaxies at their centre.

How clusters evolve

From an initial mixture of all galaxy types, collisions and mergers lead to ever larger galaxies and a predominance of elliptical galaxies (see pp.138–39). As a cluster forms, the gas in the cluster becomes hot. The hot gas surrounds and fills the space between the individual galaxies in the cluster.



1 Loose collection of galaxies
Clusters begin as a loose, uneven distribution of small galaxies of all types, gravitationally attracted to each other and towards their common centre of mass. Many of these galaxies will collide and merge.

2 Galaxies merge
When galaxies collide or merge, cold interstellar gas is energized and ejected from the galaxies, and a cloud of hot gas, mainly hydrogen, accumulates between the members of the cluster.

3 Galaxies cluster
Eventually, giant elliptical galaxies, with old stars and little gas, are densely packed around the cluster's centre, cocooned in a spherical cloud of intergalactic gas many times more massive than the galaxies' stars.

Dark matter

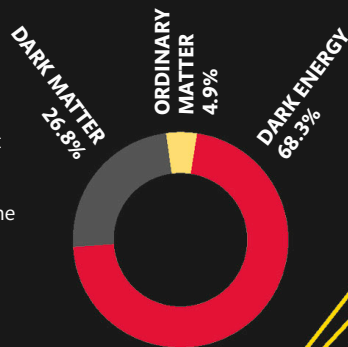
Dark matter is matter that is always invisible because, unlike ordinary matter (also called baryonic matter), it does not interact with electromagnetic radiation (see pp.152–53).

How do we know dark matter exists?

Dark matter cannot be observed directly. Instead, its presence has only been detected because of its gravitational influence on visible matter. The idea of dark matter was first put forward in the 1930s to explain why a cluster of galaxies stayed together although the gravity of the visible galaxies was not strong enough. Then, in the 1970s, the outer regions of galaxies were found to be moving far too fast, indicating invisible matter beyond was pulling them. Now scientists use a technique called gravitational lensing to detect large dark objects and X-rays to detect rises in temperature in interstellar clouds as they are compressed by dark matter.

How much is missing?

Scientists think just 5 per cent of the Universe's mass is ordinary matter. The "missing" portion is dark matter and the even more mysterious dark energy (see p.170).



Gravitational lensing

When light from distant galaxies is bent by gravity as it passes close to an intervening galaxy cluster, their images are distorted, an effect called gravitational lensing. Dark matter increases the effect, revealing its presence to astronomers and enabling them to map it.

TELESCOPE ON EARTH

WHY DO SCIENTISTS BURY THEIR DARK MATTER DETECTORS DEEP UNDERGROUND?

Detectors are buried up to 2 km (1.2 miles) underground to shield them from cosmic rays reaching Earth from space.

GALAXY CLUSTER

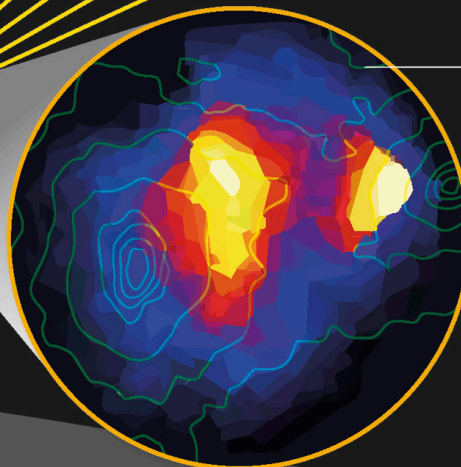
Light bent towards observer by cluster acting as lens

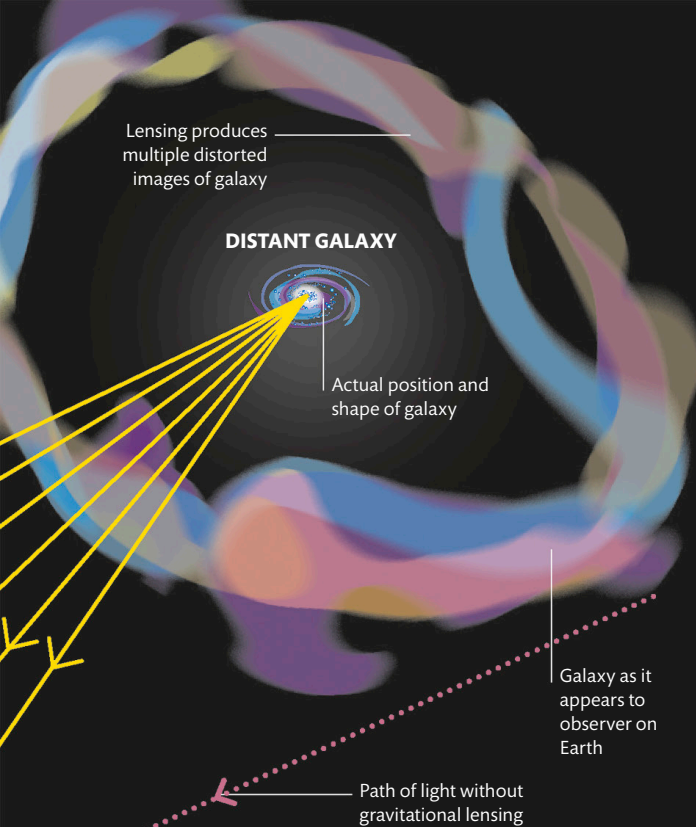
Galaxy cluster containing large amount of dark matter acts as a gravitational lens

Contour lines join points of equal dark-matter concentration

Mapping dark matter

By using software to analyse the distorted image of the distant galaxy, astronomers can create a map of the distribution of dark matter in the intervening galaxy cluster.





Types of dark matter

Scientists have envisaged two general candidates for dark matter. MACHOs are large objects made from ordinary baryonic matter that happen not to emit much light. However, these probably account for just a few per cent of all dark matter. Scientists now think that we may be entirely immersed in a sea of WIMPs – non-baryonic subatomic particles that barely interact with light at all.

TYPES OF DARK MATTER

MACHOs	WIMPs	
Some dark matter might consist of dense objects that emit so little light they can be detected only by studying gravitational lensing. Collectively called MACHOs (MASSIVE Compact Halo Objects), they include black holes and brown dwarfs. However, MACHOs cannot account for all of dark matter's mass.	Dark matter might also include Weakly Interacting Massive Particles (WIMPs), particles that are so called because they can pass through ordinary matter with little or no effect.	
	Hot	Cold
	This theoretical form of dark matter consists of particles travelling close to the speed of light.	Most dark matter, such as WIMPs, is thought to be cold – a relatively slow-moving form of matter.

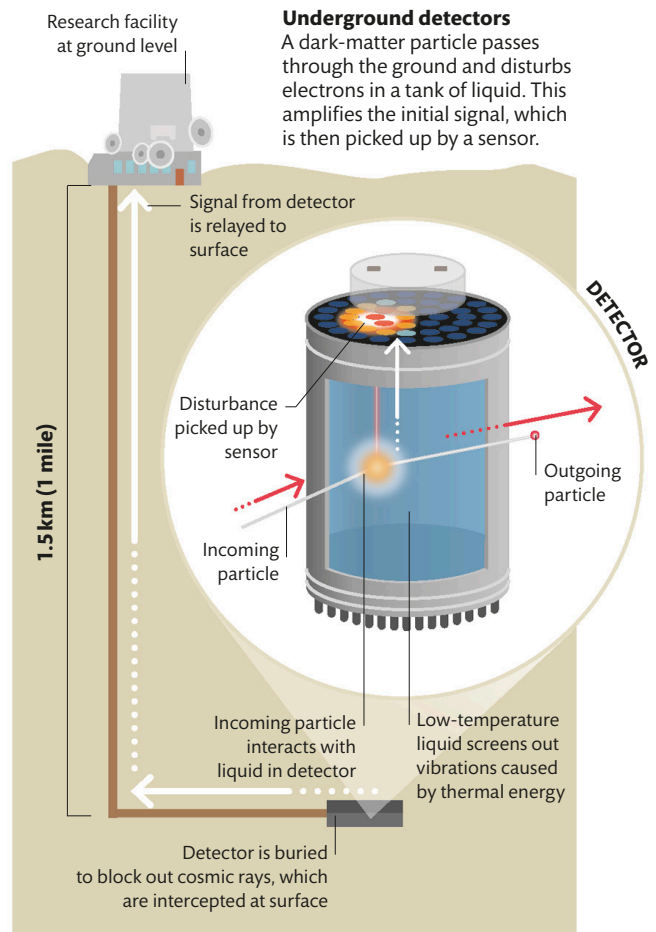
-273° C (-460° F)

THE TEMPERATURE TO WHICH SOME DARK MATTER DETECTORS HAVE TO BE COOLED



Looking for dark matter

If dark matter is subatomic particles that interact only with gravity, then detecting them is difficult. As well as studying the effects of dark matter in space, scientists are also trying to find cold dark matter particles called axions directly by using icy tanks of liquid inert elements buried far below Earth's surface.



Mapping the Universe

In the last 50 years, cosmologists have mapped the Universe in ever more detail. Powerful sky surveys have enabled them to plot similarities and differences across space and to identify vast structures.

THE LARGEST KNOWN VOID IN THE COSMIC WEB IS 2 BILLION LIGHT-YEARS ACROSS



The cosmological principle

According to the cosmological principle, on the largest scales, the Universe is the same everywhere – matter is spread evenly and obeys the same laws. It is both homogeneous (the same in wherever you are) and isotropic (the same whichever direction you look). If this is true, it means that what astronomers see in one area of the Universe is likely to be the same everywhere, and they can simply scale up. But recent observations have thrown doubt on whether it really is homogeneous.

Filaments and voids

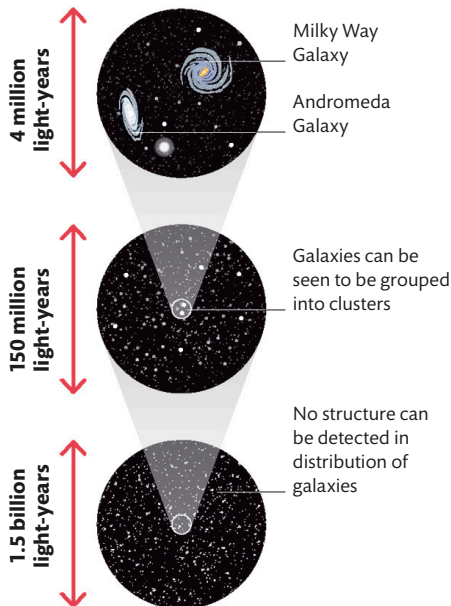
The Universe seems to be arranged like a vast cobweb, with all the stars and galaxies concentrated in threadlike filaments and sheetlike walls. In between are dark, empty voids.

Clusters of galaxies are concentrated at nodes, where filaments meet

Threadlike filaments consist mainly of hot hydrogen gas

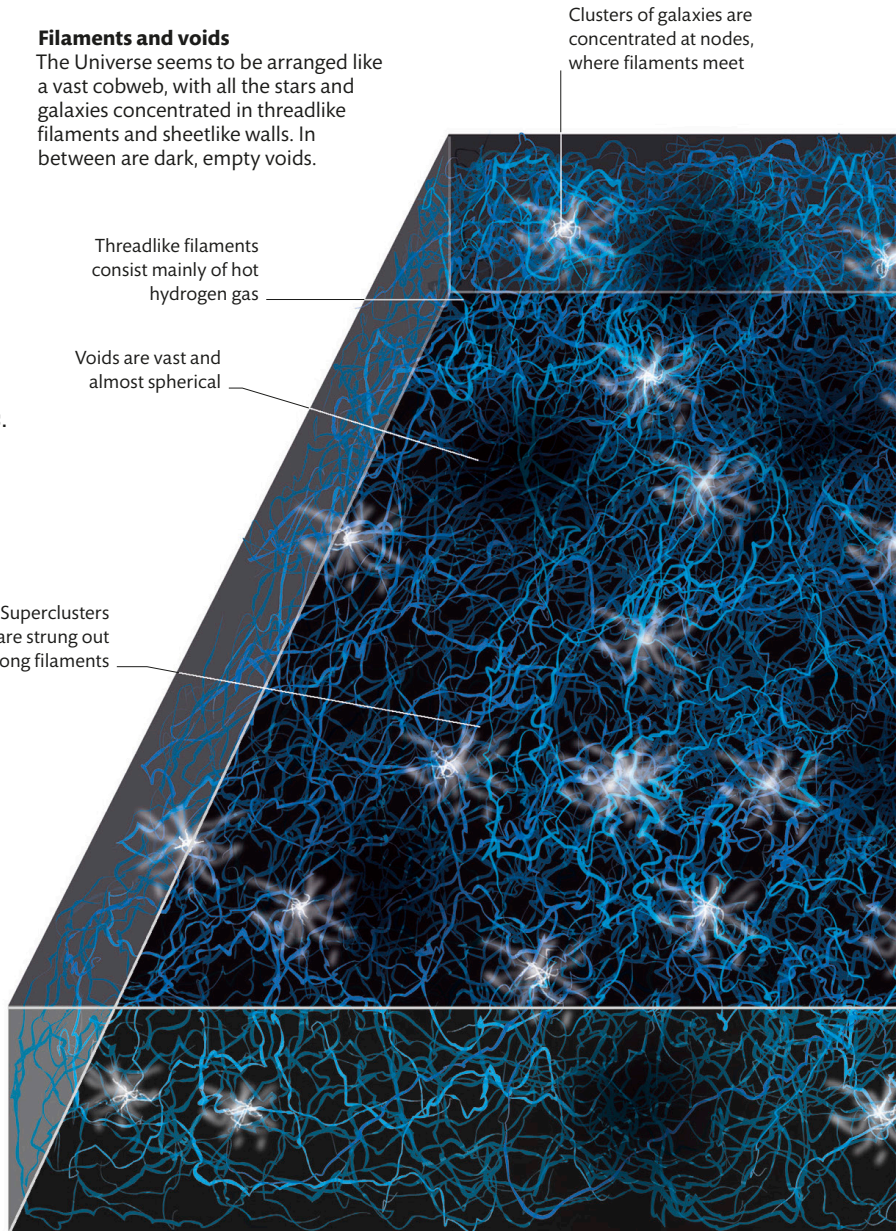
Voids are vast and almost spherical

Superclusters are strung out along filaments



Scale and structure

In theory, there are no structures at the largest scales and the differences that create structures emerge only on smaller scales.

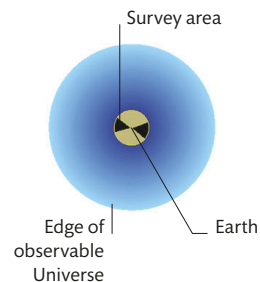


**WHAT IS THE
BIGGEST STRUCTURE
IN THE UNIVERSE?**

The largest structure of galaxies found so far is the Sloan Great Wall, nearly 1.5 billion light-years long and about 1 billion light-years from Earth.

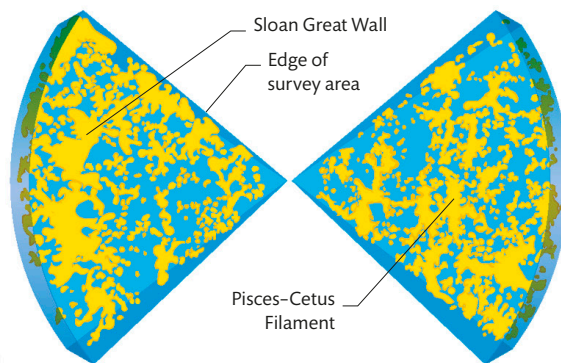
SKY SURVEYS

Much of our knowledge of the Universe's large-scale structure is based on 3D maps from surveys of samples of the observable Universe (see pp.160–61). In 2020, the Sloan Digital Sky Survey (SDSS) produced the largest, most detailed map so far, charting the history of the Universe back through 11 billion years.



The cosmic web

The Universe is not a random collection of stars and galaxies. Instead, it is a cosmic web made of connecting filaments and walls of clustered galaxies and gases stretched across the Universe, with giant voids in between, like odd-shaped bubbles. Together, these structures give the Universe a foamy appearance. However, it is thought there may be a limit on how big structures are when you zoom out far enough. This limit is sometimes called the End of Greatness.

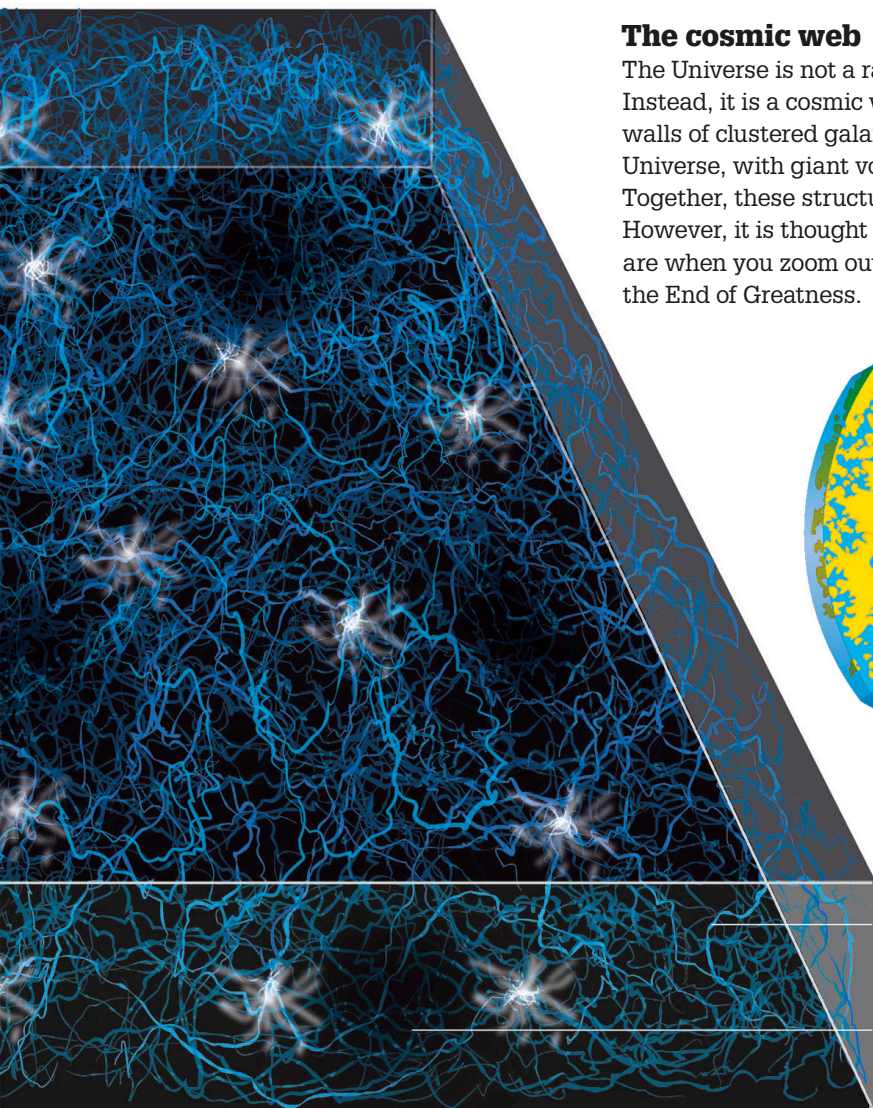


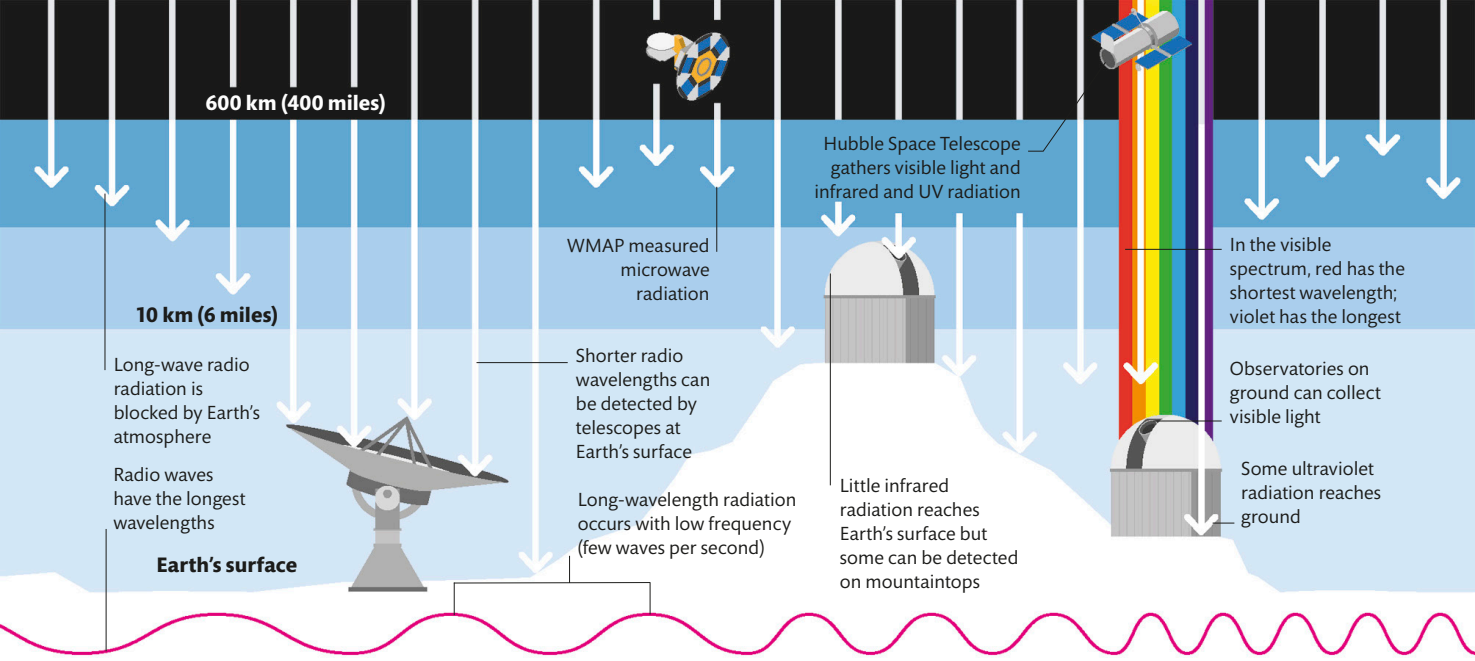
Great Walls

Filaments are long, thin threads of galaxies. In contrast, walls are wider and flatter. The length of the Sloan Great Wall, seen in this survey image, is about one-sixtieth of the diameter of the observable Universe.

Sheetlike structures are known as walls

Voids contain no galaxies or only a few and have less than 10 per cent of the Universe's average matter density





Radio waves

Stars and galaxies, as well as radio galaxies, quasars, pulsars, and masers, are all radio sources.

Microwaves

The background radiation lingering from the Big Bang is detected as microwaves.

Infrared

Infrared is heat. It can reveal dim galaxies, brown dwarfs, nebulae, and interstellar molecules.

Visible light

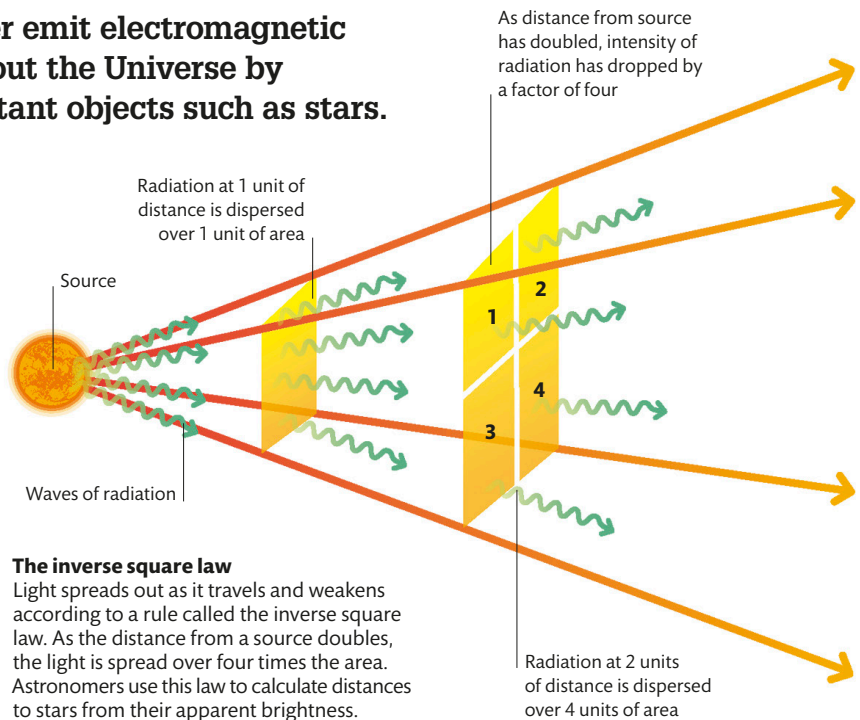
Emitted by most stars and some nebulae, and reflected by planets and clouds, light is a rich data source.

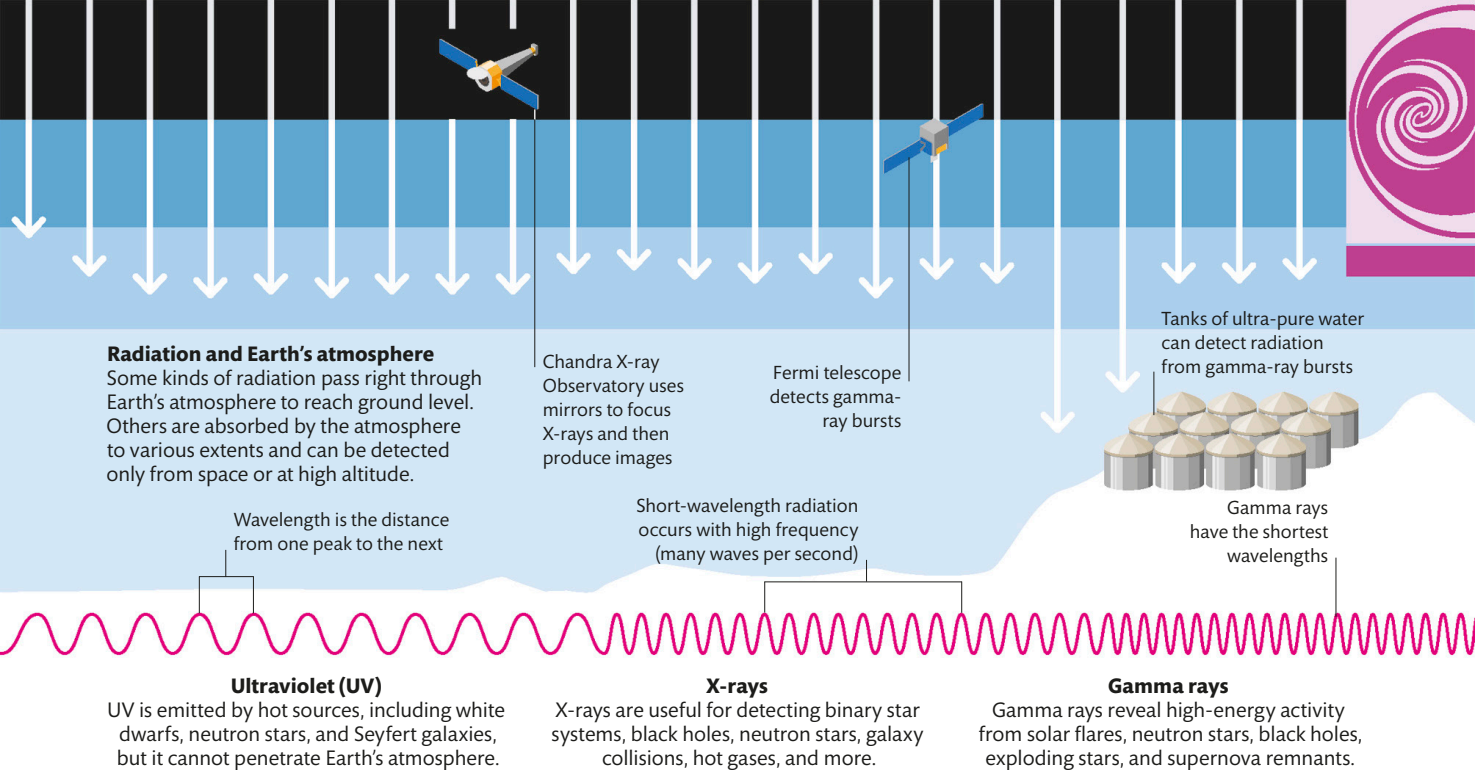
Light

Light is the electromagnetic radiation we detect with our eyes. All forms of matter emit electromagnetic radiation, and we know about the Universe by studying radiation from distant objects such as stars.

Light in space

All kinds of radiation, including light, travel through space in straight lines at the same incredible speed – 299,792 km (186,282 miles) per second – although with different wavelengths, depending on its energy. Light has no mass but can still be absorbed, reflected, or refracted when it meets something – and its path can be bent by the curved space created by a strong gravitational field (see pp.154–55). As light radiates from a source, it spreads out and its power diminishes, which is why distant galaxies appear faint.





The electromagnetic spectrum

Light is the radiation in just one wavelength band in the huge range of wavelengths called the electromagnetic spectrum. At one end are long, low-frequency waves – radio waves, microwaves, and infrared light. At the

other are short, high-frequency waves – ultraviolet light, X-rays, and gamma rays. Stars and galaxies emit all these waves in different amounts. Although the human eye can see only visible light, telescopes that can detect other wavelengths can tell us much more.

GAMMA-RAY RADIATION IS MORE THAN 100,000 TIMES MORE ENERGETIC THAN VISIBLE LIGHT

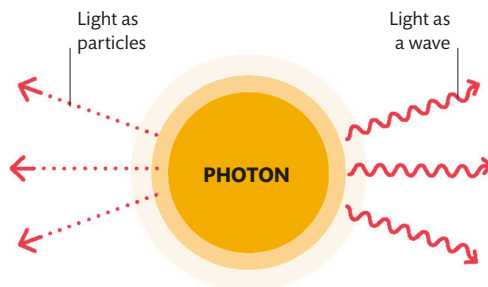


CAN ANYTHING TRAVEL FASTER THAN THE SPEED OF LIGHT?

No. According to Albert Einstein's special theory of relativity, the speed of light is the upper speed limit for ordinary matter and radiation.

PARTICLE OR WAVE?

Light and other kinds of electromagnetic radiation are emitted as packets of energy called photons. A photon is the smallest possible discrete packet, or quantum, of radiation. Photons can be understood as either particles or waves, depending on how they are encountered. This two-fold nature of light is referred to as wave-particle duality.



Space-time

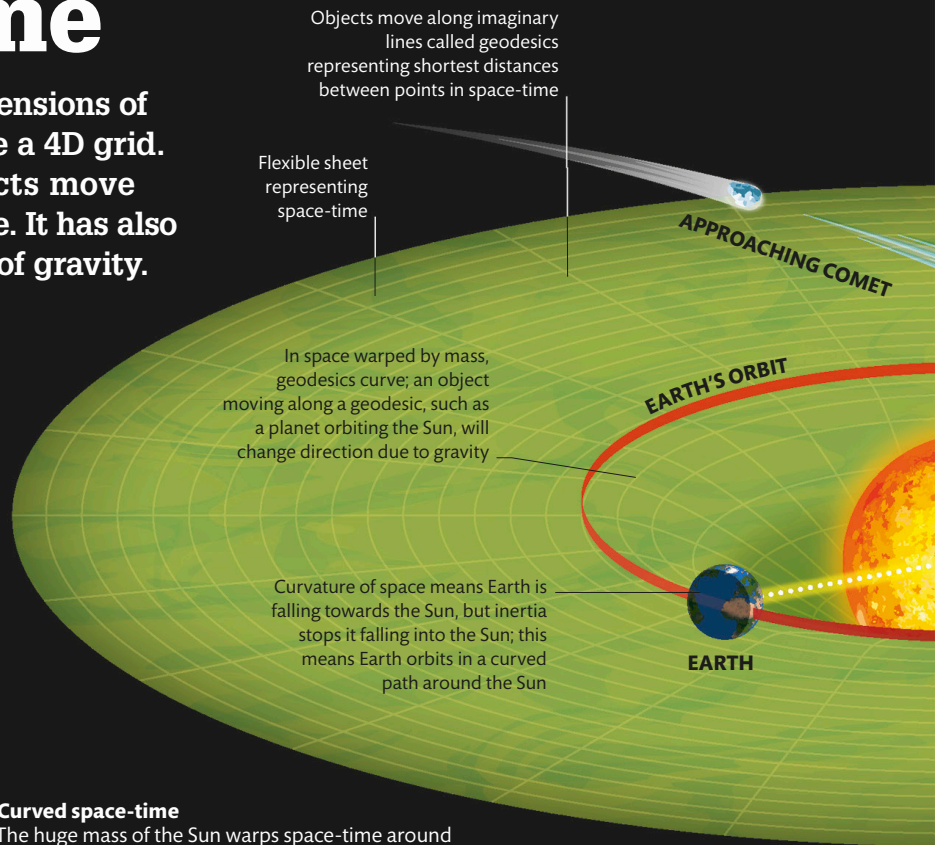
In space-time, the three dimensions of space join with time to make a 4D grid. This idea reveals how objects move through time as well as space. It has also changed our understanding of gravity.

What is space-time?

In space-time, time and space are inseparably joined to form a grid that scientists often liken to a sheet of rubber. The sheet has two dimensions but represents four-dimensional space-time and shows bends in time as well as space. In his general theory of relativity, Albert Einstein showed how space-time is warped around objects with mass. The more massive the object, the greater the distortion. This warping controls how everything in the Universe moves, even light. Gravity, Einstein realized, is simply the effect of these distortions on the way things move.

Curved space-time

The huge mass of the Sun warps space-time around it like a heavy ball on a rubber sheet. Objects moving through its gravitational field, such as Earth, comets, and even light, are bent towards it.

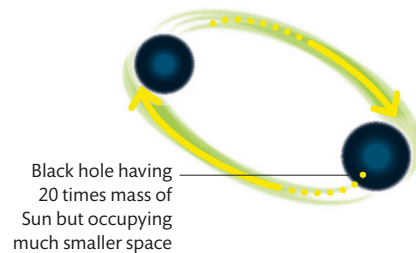


Gravitational waves

In 1916, Einstein predicted that massive, accelerating objects might send out ripples in the fabric of space-time. Scientists now think that these ripples, known as gravitational waves, are set off by cataclysmic events in space – such as supernovae and colliding neutron stars and black holes – and that they travel away from their sources at the speed of light. Although they are hard to detect, gravitational waves may in future provide an alternative to electromagnetic radiation as a way of seeing things in space, such as black holes and dark matter.

Ripples from black holes

The existence of gravitational waves was confirmed in 2015, when ripples from two black holes colliding 1.3 billion light-years away were picked up on Earth using a technique called laser interferometry.

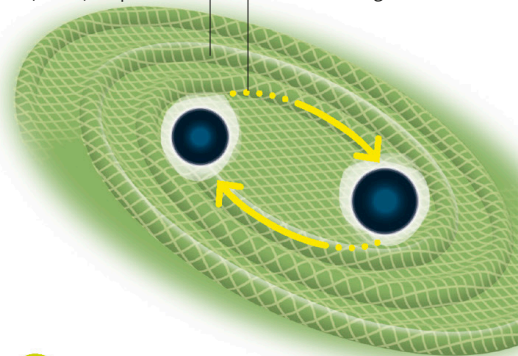


1 Colliding black holes

The two black holes were the remnants of collapsed giant stars. As they came close, they orbited each other for maybe millions of years before causing significant ripples.

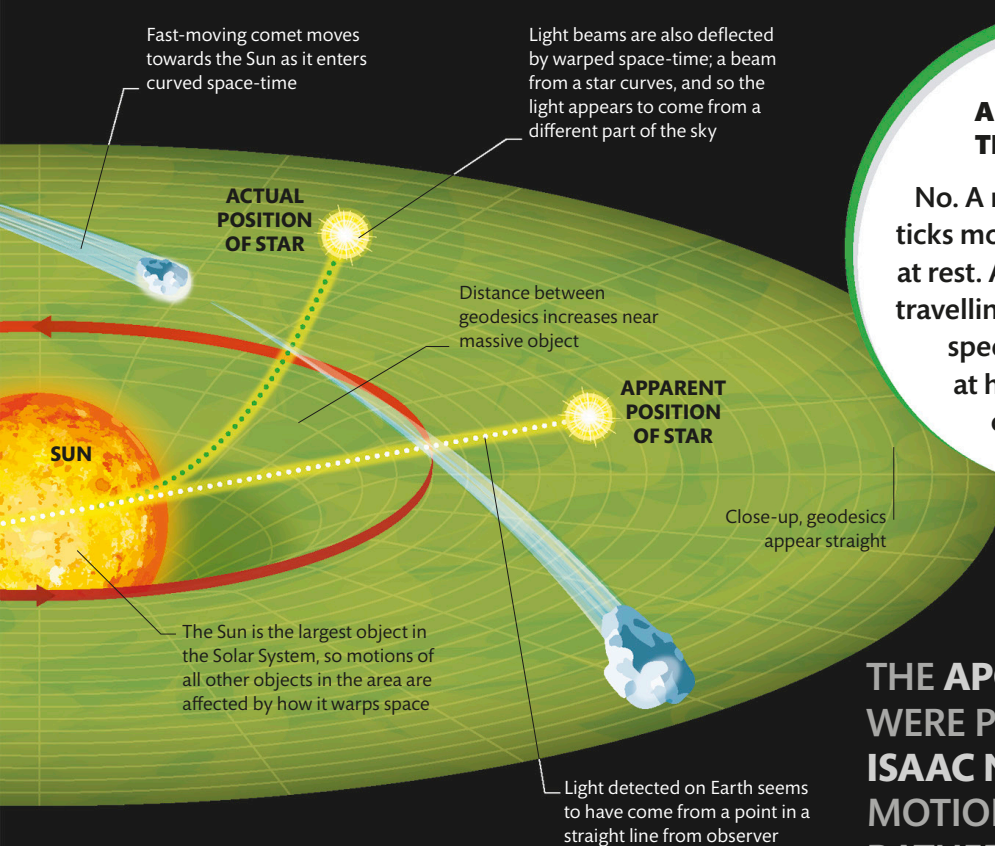
Fast-moving black holes make ripples (waves) in space-time

Black holes move gradually faster and come closer together



2 Orbital speed increases

As the black holes came closer, they began to send gravitational waves out through the surrounding space-time. This released energy, allowing them to orbit closer and faster.

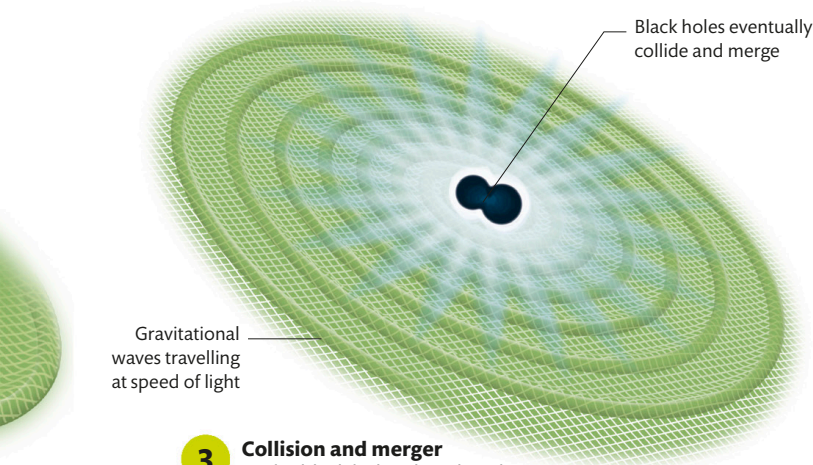


DOES TIME ALWAYS PASS AT THE SAME RATE?

No. A rapidly moving clock ticks more slowly than a clock at rest. A clock on a spaceship travelling at 87 per cent of the speed of light will tick at half the speed of a clock on Earth.



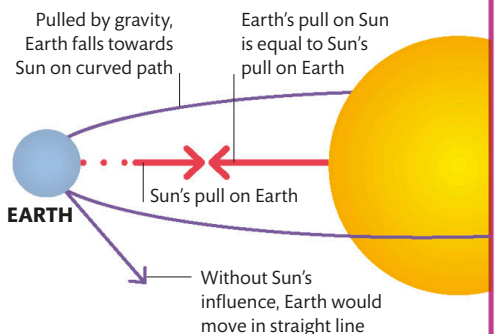
THE APOLLO MISSIONS WERE PLANNED USING ISAAC NEWTON'S LAWS OF MOTION AND GRAVITATION RATHER THAN EINSTEIN'S



3 Collision and merger
As the black holes closed in, they emitted more waves, losing more energy and eventually becoming locked into a runaway collision. The final crunch sent massive shockwaves out through space-time.

NEWTON'S GRAVITY

Newton explained gravity as a mutual attraction between all matter. He asserted that Earth is held in its orbit by a balance between gravity and its own momentum.



Looking back in time

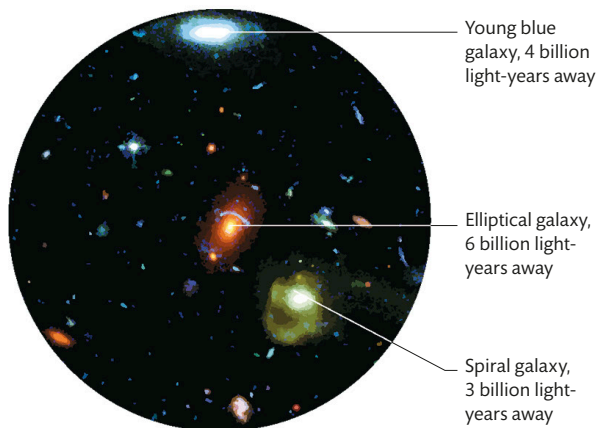
When we look into space, the stars and galaxies we see are vast distances away. Looking at them means we are also looking back in time, seeing them as they were when the light left them.

Lookback time

Although light moves faster than anything else in the Universe – at about 300,000 km (190,000 miles) per second – it does not reach us instantaneously. The further away an object is, the longer light takes to reach us, so the further back in time we are seeing. An object's lookback, or time-travel, distance (see pp.160–61) is also a measure of how long its light has been travelling to us – its lookback time.

How far away in time and space?

Even light from nearby objects, such as those in the Solar System, takes an appreciable time to reach us. Light takes more than eight minutes to arrive from the Sun and 1.3 seconds from the Moon.

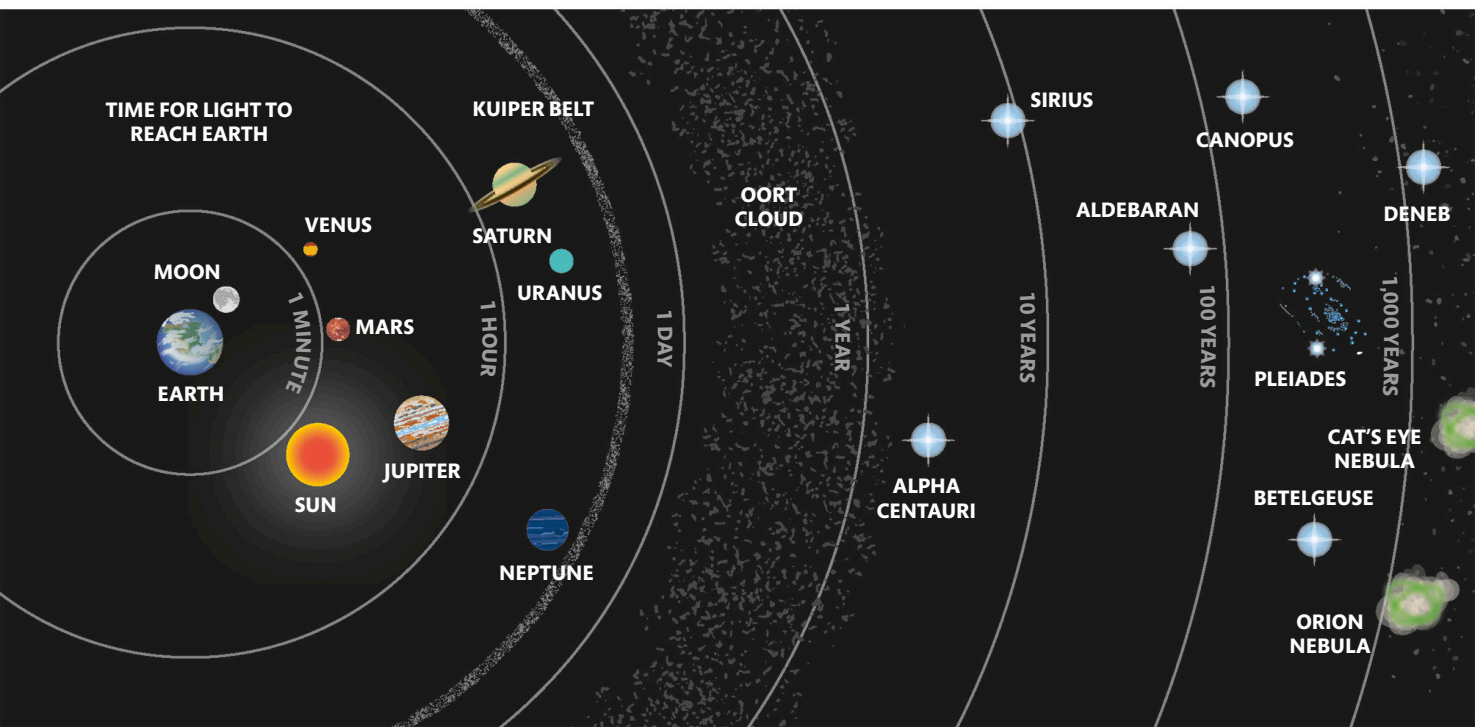


Looking into deep space

The Hubble Deep Field images of galaxies billions of light-years away reveal how the galaxies appeared billions of years ago.

Seeing into deep time

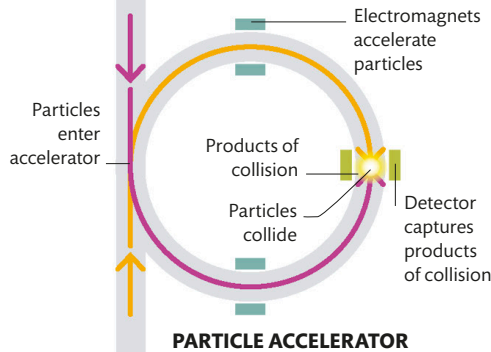
One of the most distant objects readily visible to the naked eye is the Andromeda galaxy. It is about 2.5 million light-years away, which means that we see it as it was 2.5 million years ago. With the Hubble Space Telescope, we can see objects billions of light-years away and therefore as they were billions of years ago. Light from such distant objects has been red-shifted (see p.159), so that it may only be possible to observe them in the infrared part of the spectrum.



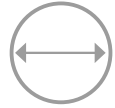


THE EARLIEST MOMENTS OF THE UNIVERSE

Although we cannot directly observe the earliest moments of the Universe, we can investigate what they might have been like by using particle accelerators (such as the Large Hadron Collider) to smash together subatomic particles and recreate the conditions that are thought to have existed immediately after the Big Bang.



GALAXY GN-Z11
IS ONE OF THE
MOST DISTANT
OBJECTS EVER
DETECTED - WE
SEE IT AS IT
WAS ABOUT
13.4 BILLION
YEARS AGO



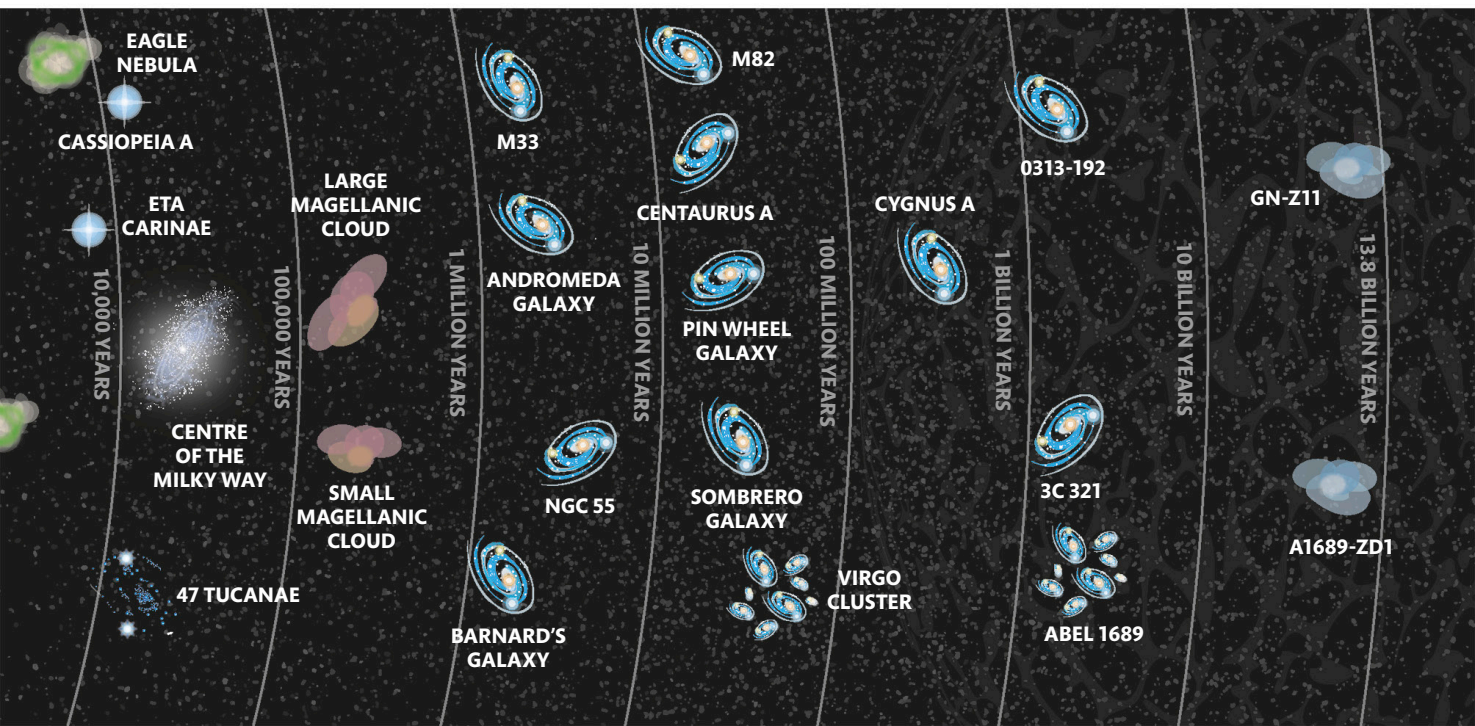
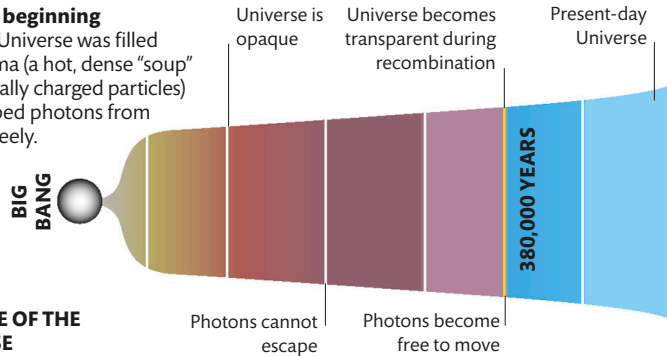
The limit of deep time observation

Light particles (photons) could not travel freely in the early Universe, so we cannot observe it directly. About 380,000 years after the Big Bang, in a period known as recombination (see pp.164–65), photons became able to move freely. These photons form the cosmic microwave background and are the oldest it is possible to detect.

The dark beginning

The early Universe was filled with plasma (a hot, dense "soup" of electrically charged particles) that stopped photons from moving freely.

TIMELINE OF THE UNIVERSE

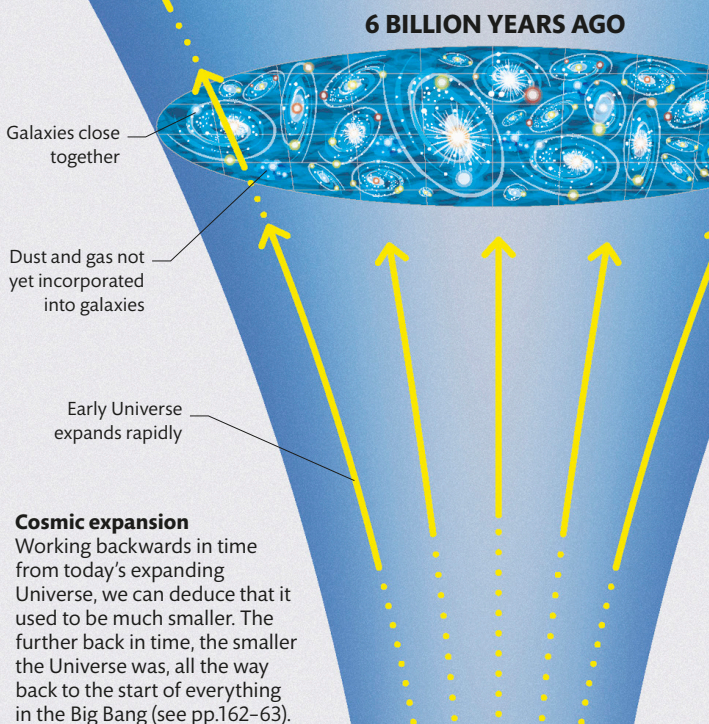
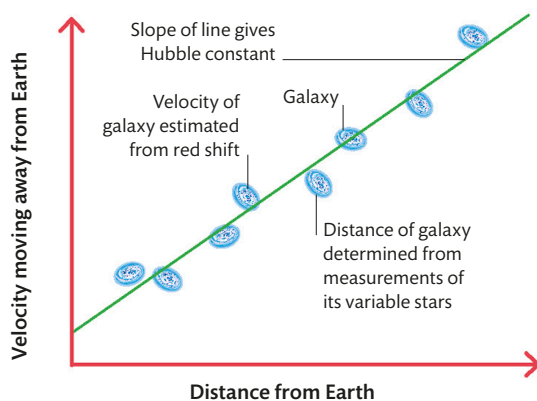


WILL THE UNIVERSE EXPAND FOREVER?

There are four main possible futures for the Universe: it might continue expanding, expand then contract, be ripped apart, or change into a different Universe (see pp.170–71).

THE HUBBLE-LEMAÎTRE LAW

In 1927, Georges Lemaître predicted that the Universe is expanding and that this accounted for the known red shifts of galaxies (see opposite). Around the same time, Edwin Hubble used observations of Cepheid variable stars (see p.99) to estimate the distances to several galaxies. He realized that the more distant galaxies were moving away faster. This is known as the Hubble-Lemaître law. Plotting velocity against distance produced a straight line. The line's slope is a measure of the rate of expansion of the Universe, called the Hubble constant.



Cosmic expansion

Working backwards in time from today's expanding Universe, we can deduce that it used to be much smaller. The further back in time, the smaller the Universe was, all the way back to the start of everything in the Big Bang (see pp.162–63).

ALTHOUGH SPACE IS EXPANDING, THE OBJECTS WITHIN SPACE STAY THE SAME SIZE

The expanding Universe

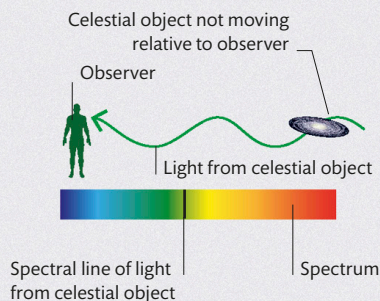
Every second, the distance between objects in the Universe is getting bigger, like dots on the surface of a balloon that is being blown up. This is because the very fabric of space itself is expanding. We know that the rate of expansion is speeding up, but we do not know why or exactly how quickly.

The nature of expansion

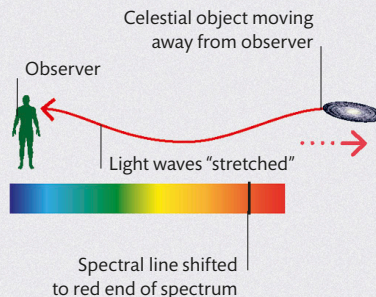
Galaxies and other celestial objects are not moving away from each other through space. Instead, space itself is expanding and carrying the objects with it, although in localized regions objects may move towards each other if their gravitational attraction is strong enough. There are two methods for calculating how fast the Universe is expanding: using the cosmic microwave background radiation (see pp.164–65); and measuring the red shift in the light from certain stars. The methods give different results, but a generally accepted estimate is that the Universe is expanding at about 20 km (12 miles) per second every million light-years.

Movement and wavelength

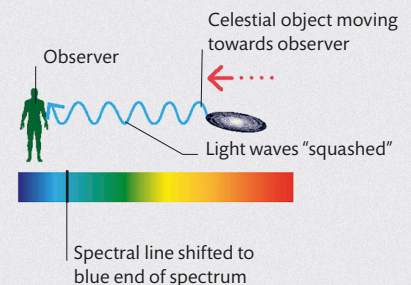
When an object and an observer are not moving relative to each other, the observer sees the true wavelength of light from the object. But if they are moving apart, the wavelength becomes longer, an effect called red shift; if they are moving closer to each other, the wavelength becomes shorter, known as blue shift.



OBSERVER AND OBJECT STATIONARY



OBSERVER AND OBJECT MOVING APART



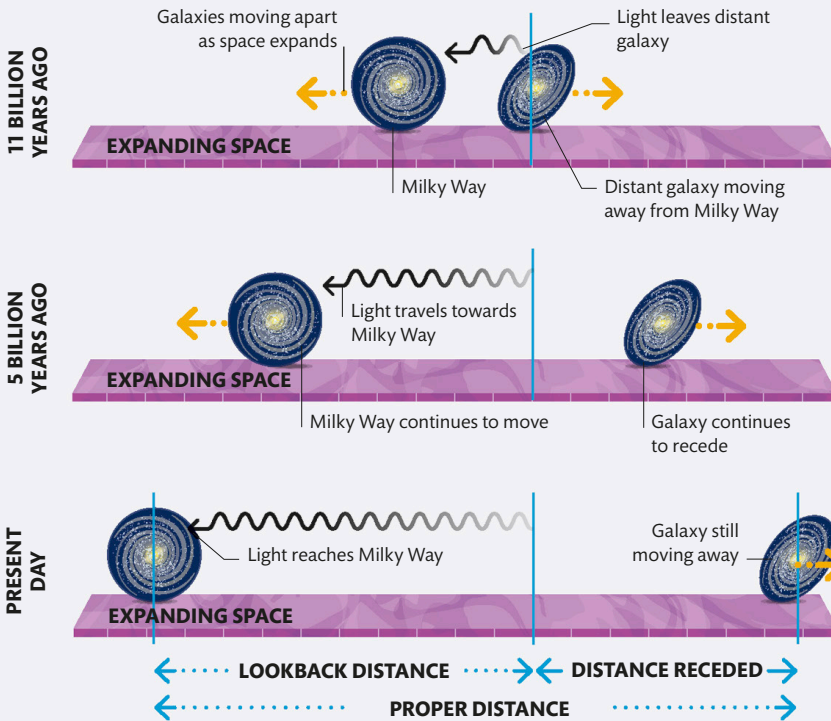
OBSERVER AND OBJECT MOVING CLOSER TOGETHER

Measuring distance

Space is expanding, so the current distance to an object in space, called its proper distance, is greater than the distance light from the object has travelled to reach us, known as the lookback distance. However, when astronomers give the distances of objects, that figure is usually the lookback one, because the exact proper distance depends on the rate of expansion of the Universe (see pp.158–59), which is uncertain.

Lookback and proper distance

The lookback distance is how far light has travelled from an object to reach us today. The proper distance is the true distance from us to the object. It is greater than the lookback distance due to the Universe's expansion.



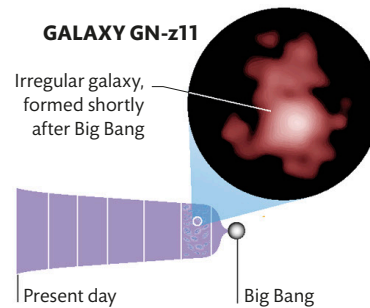
HOW BIG IS THE UNIVERSE?

The Universe is bigger than the part we can observe. We do not know exactly how much bigger, but some models estimate that it could be a sphere at least 7 trillion light-years across.

Current distance from Earth of the most distant visible objects in the Universe that are theoretically visible

THE FURTHEST VISIBLE GALAXY

Detected by the Hubble Space Telescope in 2016, GN-z11 is the most distant galaxy observed from Earth. Formed about 400 million years after the Big Bang, it is located at a lookback distance of about 13.4 billion light-years. During the time taken for its light to reach us, the Universe has expanded and GN-z11 is now at a proper distance from Earth estimated to be 32 billion light-years.



TIMELINE OF THE UNIVERSE

Region beyond observable Universe

How far can we see?

The Universe is expanding and has been since its beginning in the Big Bang. This means there is a huge region, possibly infinitely large, that we cannot see because light has not had enough time to reach us from those distant parts.

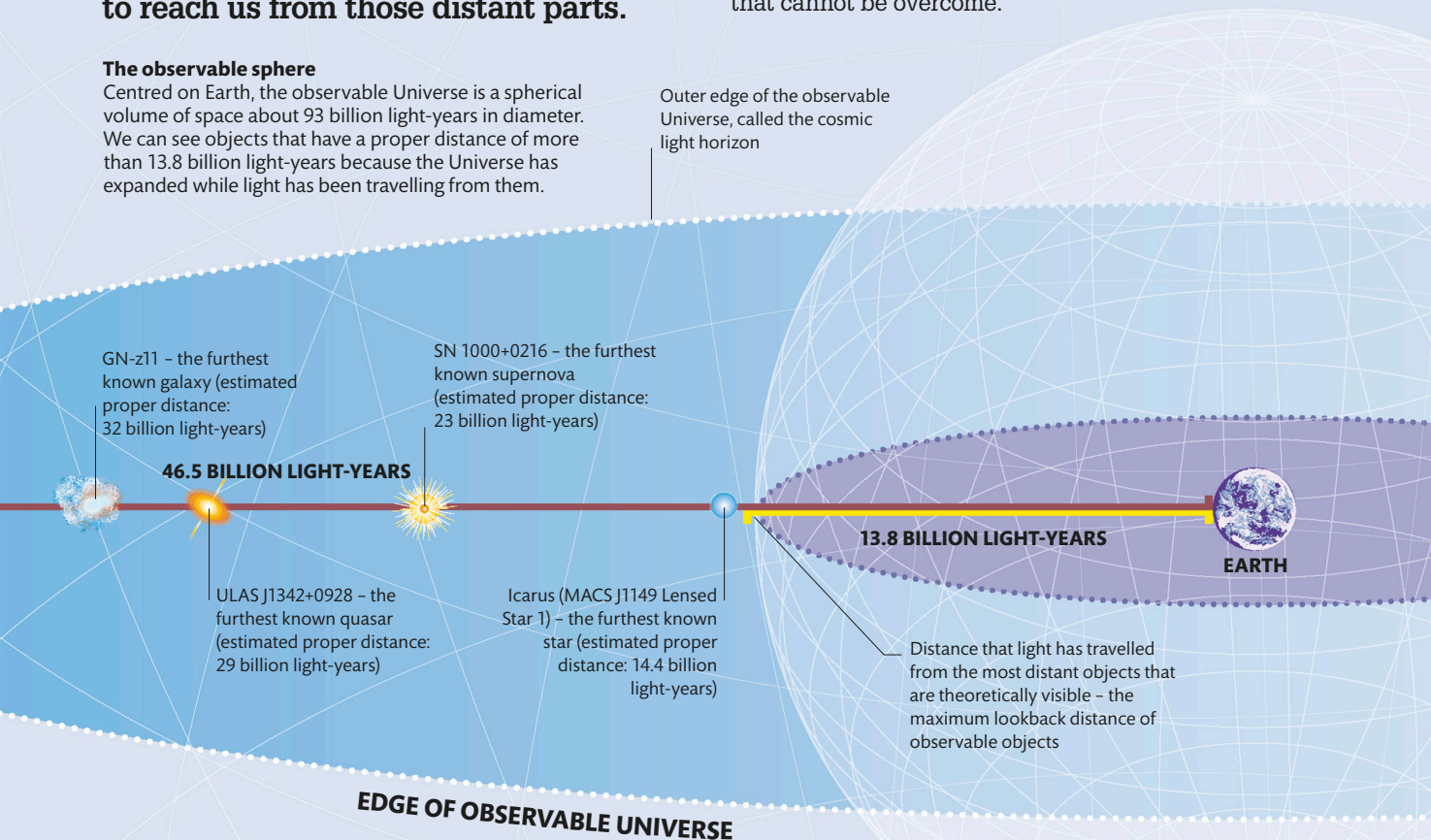
The observable sphere

Centred on Earth, the observable Universe is a spherical volume of space about 93 billion light-years in diameter. We can see objects that have a proper distance of more than 13.8 billion light-years because the Universe has expanded while light has been travelling from them.

The observable universe

Extending 46.5 billion light-years from Earth in every direction is a region of space called the observable Universe. This spherical region makes up every part of the Universe we have the potential to see, because light has had enough time (the age of the Universe, or 13.8 billion years) to reach us.

The size of the observable Universe does not depend on the ability of our technology to detect distant objects. Instead, it is a limit resulting from the Universe's age and the finite speed of light, both of which are fundamental physical properties that cannot be overcome.



LIGHT FROM ANYTHING MORE THAN 60 BILLION LIGHT-YEARS AWAY WILL NEVER REACH EARTH



The Big Bang

Today, the Universe is teeming with stars, planets, and galaxies, but it started life about 13.8 billion years ago as an infinitely tiny speck that began expanding and is still growing.

The beginning

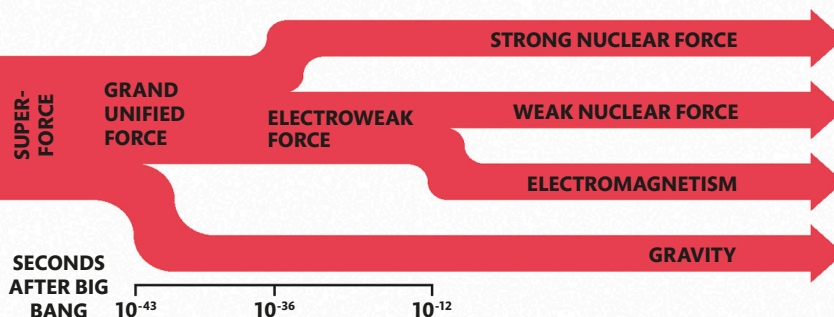
Wind back the expansion of the Universe and everything gets crammed into a very small space – a singularity. This super-hot, super-dense beginning is called the Big Bang. In the first fractions of a second, the singularity grew at faster than light-speed in a period known as inflation, at the end of which the Universe consisted of a sea of particles and antiparticles. The Universe then continued to expand, but at a slower rate, and eventually developed into the cosmos we are familiar with today.

The birth of the Universe

The Big Bang was not an enormous explosion in space but an incredibly fast expansion from a single point. Everything in the modern Universe was in that point, which is why astronomers say that the Big Bang happened everywhere at once.

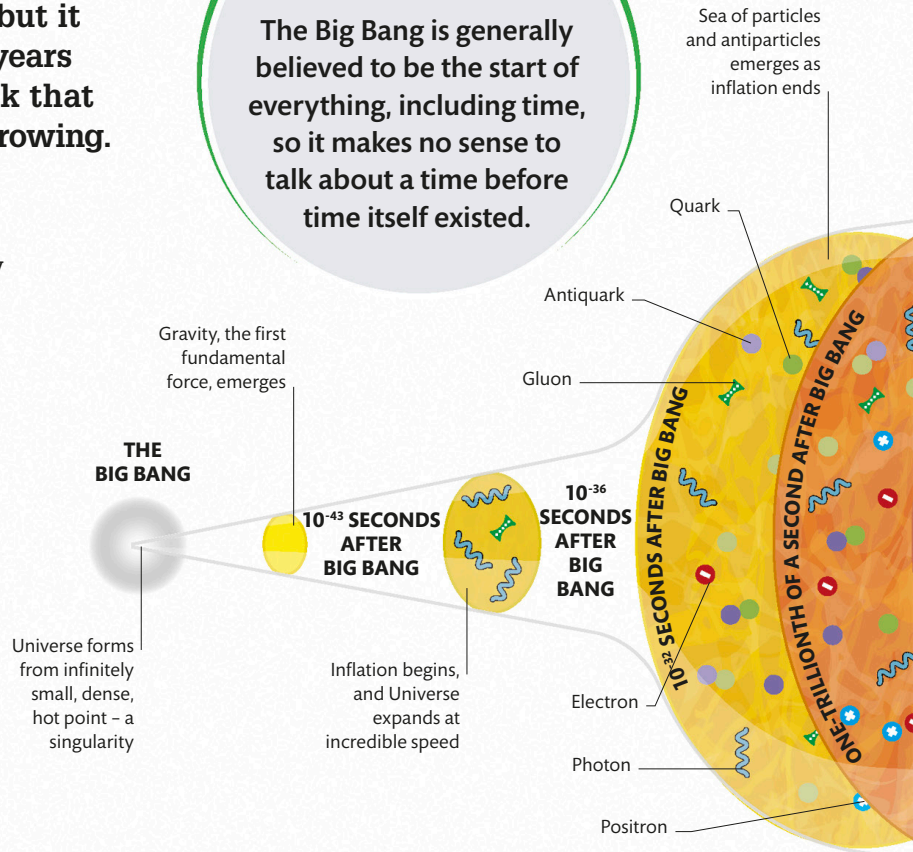
Fundamental forces

In the first instants after the Big Bang, there was only energy; matter did not exist. In the present, four fundamental forces are at work, but these were initially unified into a single superforce. The four forces soon peeled off the superforce until they had completely separated out by one-trillionth of a second (10^{-12} seconds) after the Big Bang.



WHAT WAS BEFORE THE BIG BANG?

The Big Bang is generally believed to be the start of everything, including time, so it makes no sense to talk about a time before time itself existed.

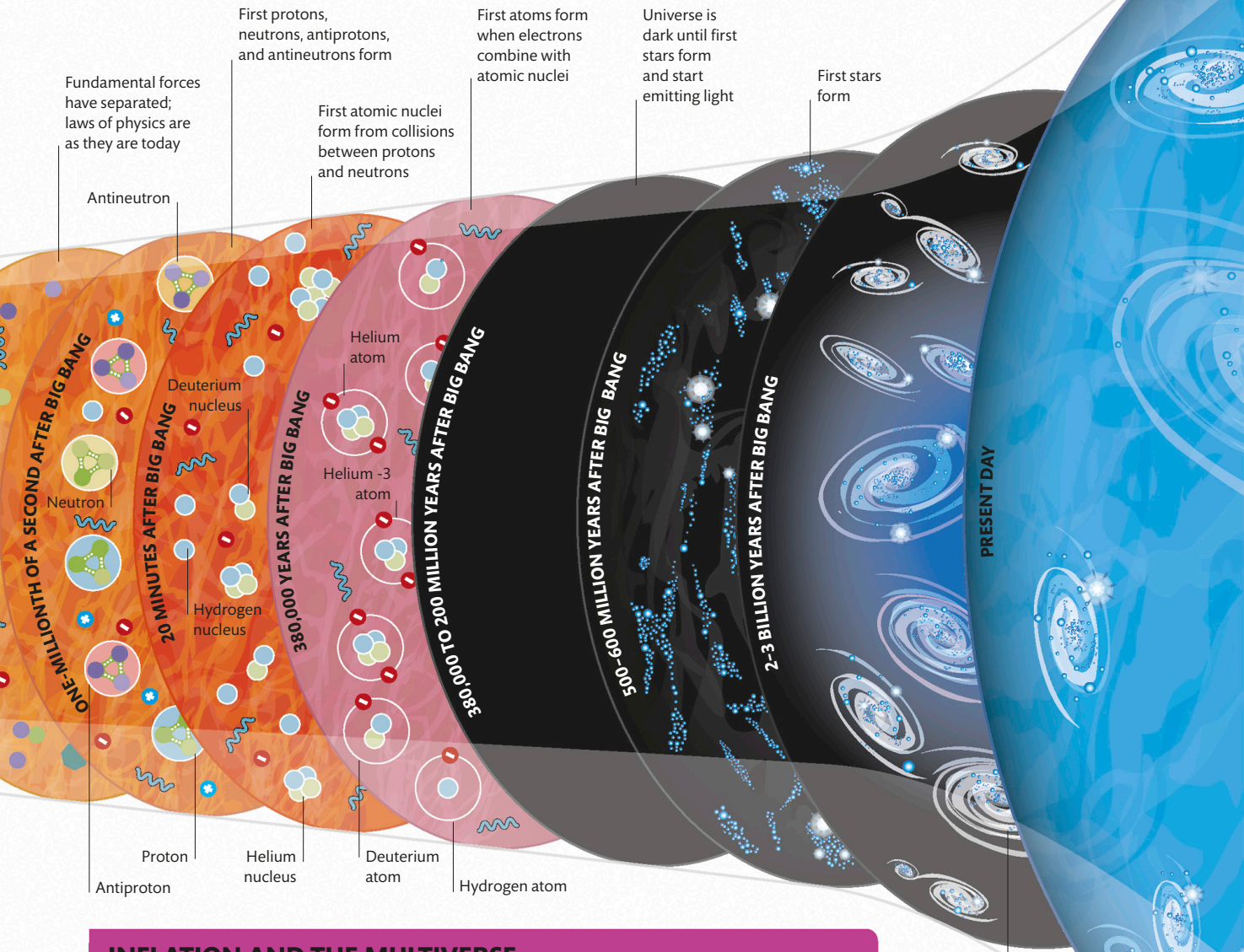


IF INFLATION WAS REPEATED TODAY, A CELL WOULD GROW LARGER THAN THE OBSERVABLE UNIVERSE



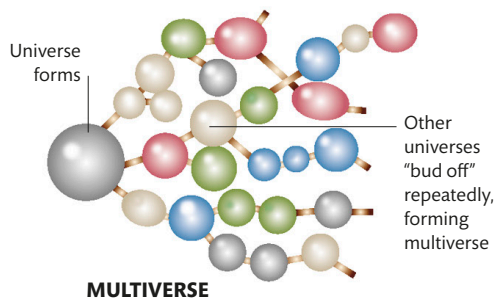
The separation of forces

Physicists believe that the four fundamental forces that govern how particles interact (the strong nuclear force, electromagnetism, and gravity) and how radioactive decay occurs (the weak nuclear force) were originally one single force but separated out soon after the Big Bang, although they do not yet know how the separation occurred.



INFLATION AND THE MULTIVERSE

Physicists searching for a mechanism for inflation have found it difficult to get it to occur only once in simulations. It seems that inflation is more likely to be eternal, constantly creating new universes – a multiverse. However, this idea remains controversial and there is no obvious way of testing it experimentally.



Universe continues to expand

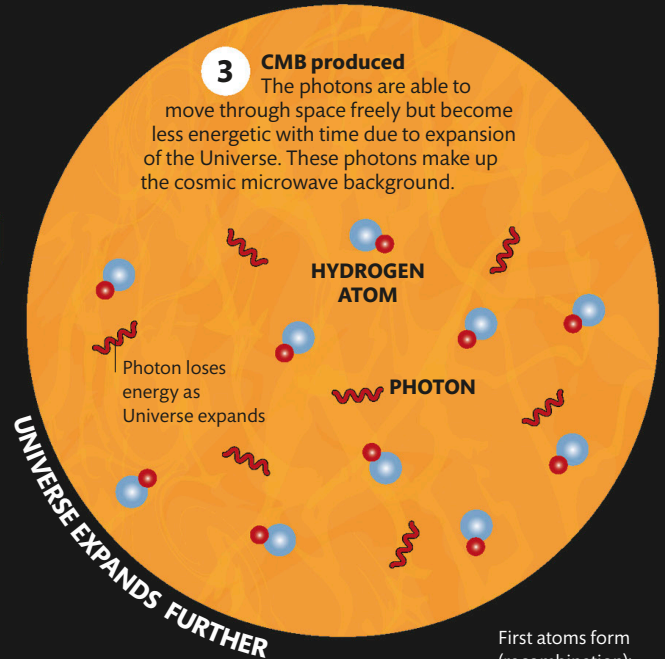
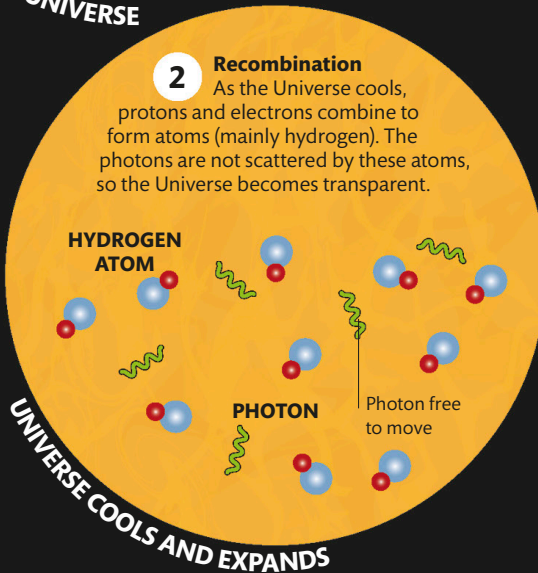
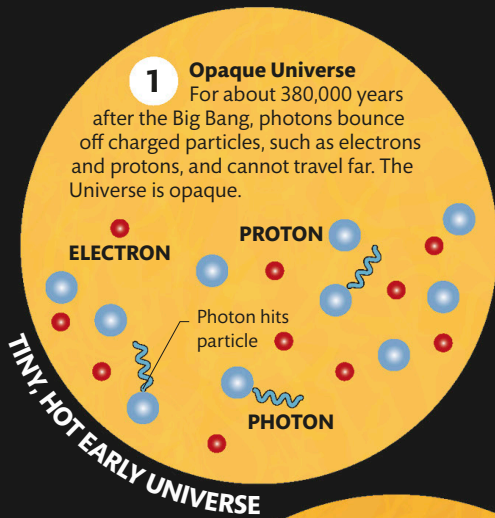
Recombination

The early Universe was too hot for protons and electrons to exist combined as atoms and too dense for photons to move freely. As the Universe expanded, it cooled and became less dense. Starting about 380,000 years after the Big Bang, in a period known as recombination, it cooled and expanded sufficiently to enable protons and electrons to combine to form hydrogen atoms and photons to travel freely.

The origin of the CMB

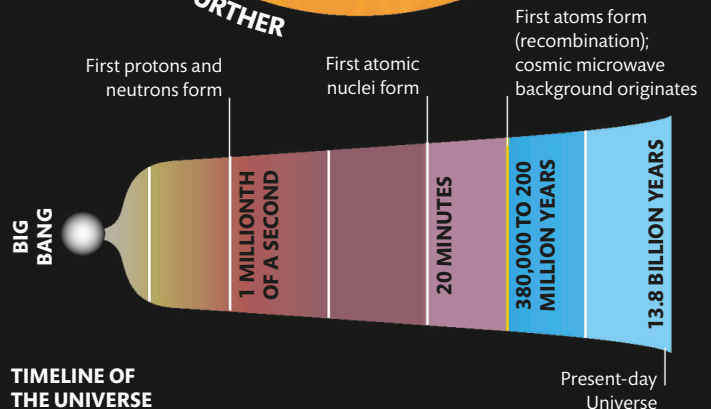
After recombination, the Universe was filled with small atoms (mainly hydrogen but also small amounts of helium and lithium). The atoms did not block photons (light particles) like the dense plasma did before, and they could travel freely. These photons can be detected now, as the CMB radiation.

**THE CMB EVERYWHERE
IS AT AN AVERAGE
TEMPERATURE OF
-270.425°C
(-454.765°F)**



Early radiation

The very early Universe was opaque. Light could only move freely once the first atoms had formed. The relic radiation from this period forms the cosmic microwave background (CMB) and is the earliest radiation we can detect.



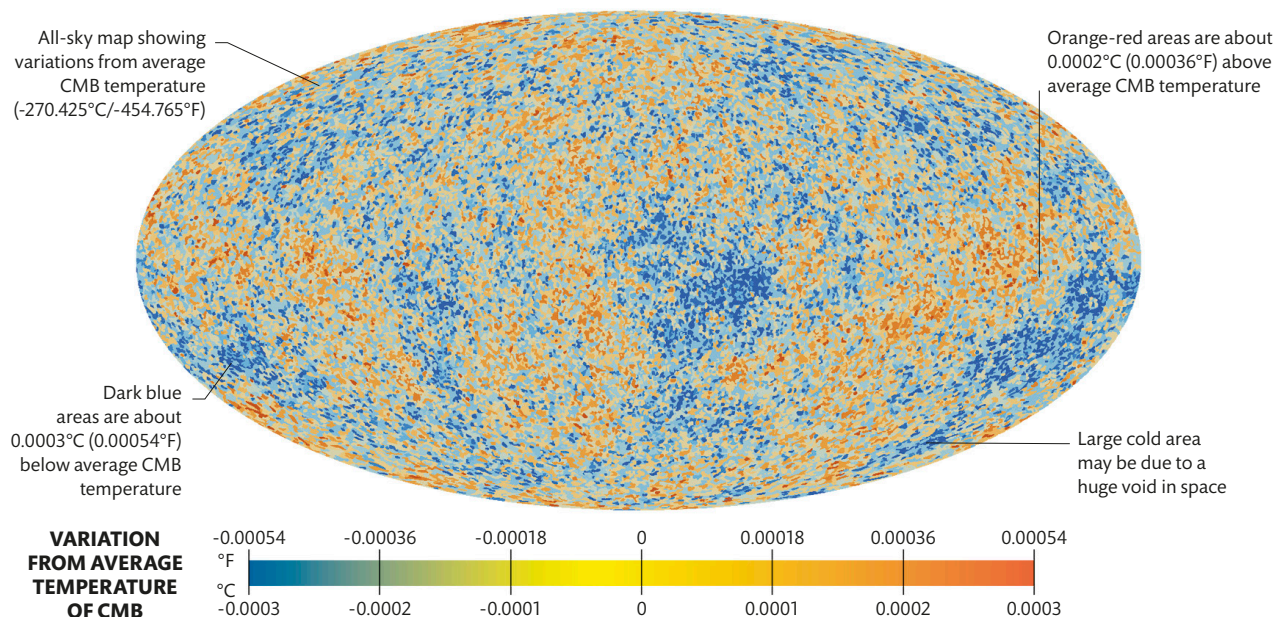


Measuring the CMB

Since the discovery of the CMB in 1964, hundreds of experiments have been conducted to measure and study the radiation. The most complete picture was put together using data gathered by Europe's Planck space observatory, from 2009 to 2013. The CMB looks almost identical in every direction but has tiny fluctuations that differ in temperature by only a fraction of a degree. These represent differences in densities that were present right after the Universe formed. They started as tiny variations but, as the Universe expanded, the fluctuations grew along with it, and areas with higher density in the early Universe turned into huge structures like galaxy clusters.

The earliest radiation

This image, obtained by the Planck observatory, shows the whole sky projected onto a flat surface. The temperature variations relate to irregularities in the density of matter in the early Universe. Areas of higher-than-average temperature indicate areas of higher density, and vice versa.



OTHER EVIDENCE FOR THE BIG BANG THEORY

The existence of the cosmic microwave background radiation provides strong evidence in support of the Big Bang theory of the origin of the Universe. Other observations also provide support for the theory.



EXPANSION

The Universe is known to be expanding and cooling. This implies that the Universe must originally have been much smaller and hotter than it is now, as predicted by the Big Bang theory.



ELEMENTS

The proportions of elements (notably the lighter elements hydrogen, helium, and lithium) present in the modern Universe correspond to those predicted by the Big Bang theory.



NIGHT SKY

If the Universe were infinitely large and old, the night sky would look bright. The fact that it does not is known as Olber's paradox. The paradox is resolved by the Big Bang's theory that the Universe has not always existed.

WHY IS THE CMB SO COLD?

Originally, the CMB had a much shorter wavelength and higher energy, corresponding to about 3,000°C (5,400°F). As the Universe expanded, the radiation was stretched to longer wavelengths, which have less energy and so are colder.

Early particles

Shortly after the Big Bang, the first particles emerged from a sea of energy. They would go on to form the building blocks of the modern Universe.

The first nuclei

Initially the Universe was inconceivably hot, and matter and energy were in an interchangeable form known as mass-energy. As the cosmos cooled, fundamental particles, including quarks (see opposite), emerged. The strong nuclear force (see p.162) bound quarks together to form protons and neutrons, which make up the nuclei of all atoms.

The origin of matter

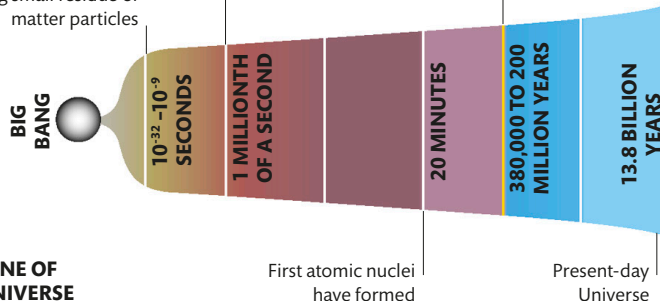
By the time the Universe was just 20 minutes old, the first atomic nuclei had formed. Matter and antimatter (see opposite) were both present, in the form of particles and antiparticles.

Particles and antiparticles form and then annihilate each other, creating energy and leaving small residue of matter particles

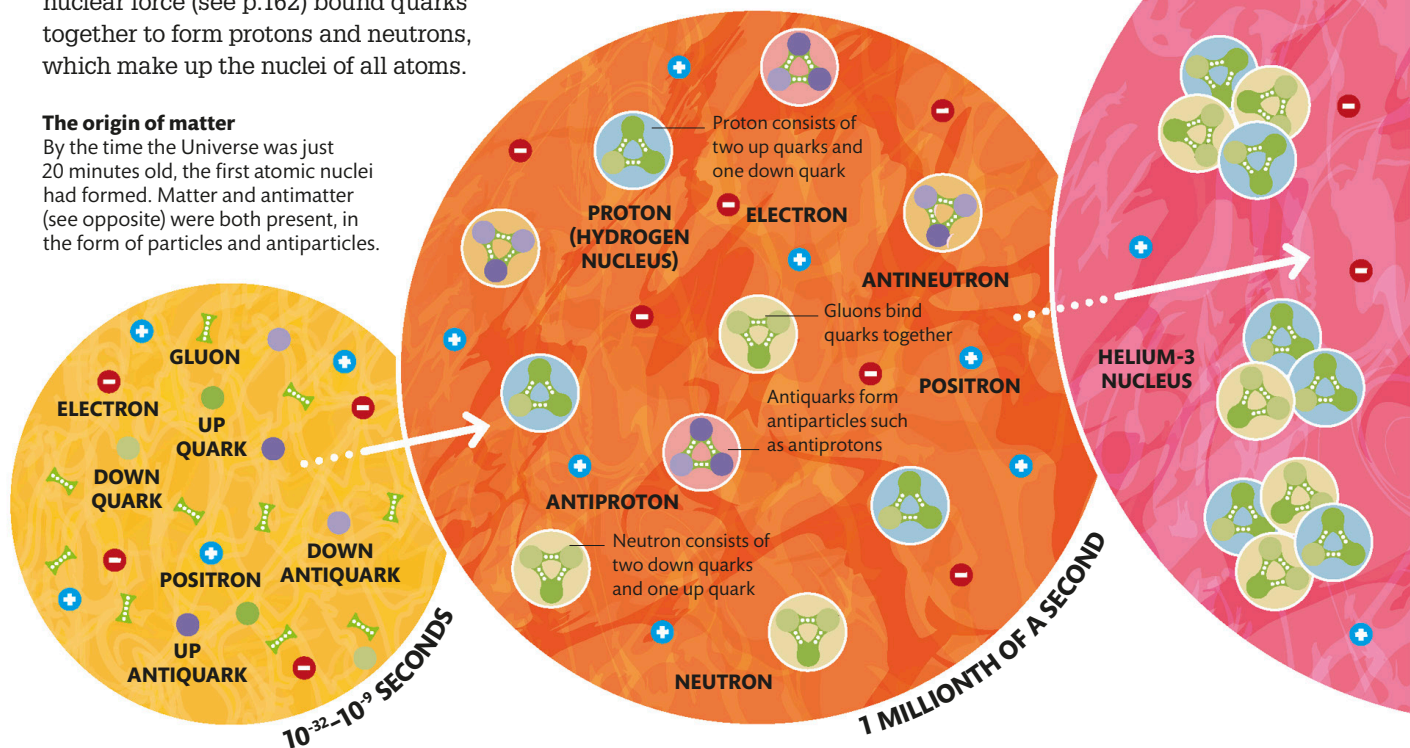
First protons and neutrons form

First atoms form (recombination)

TIMELINE OF THE UNIVERSE



THE HYDROGEN NUCLEI IN A GLASS OF WATER WERE CREATED IN THE FIRST FEW MINUTES OF THE UNIVERSE'S LIFE



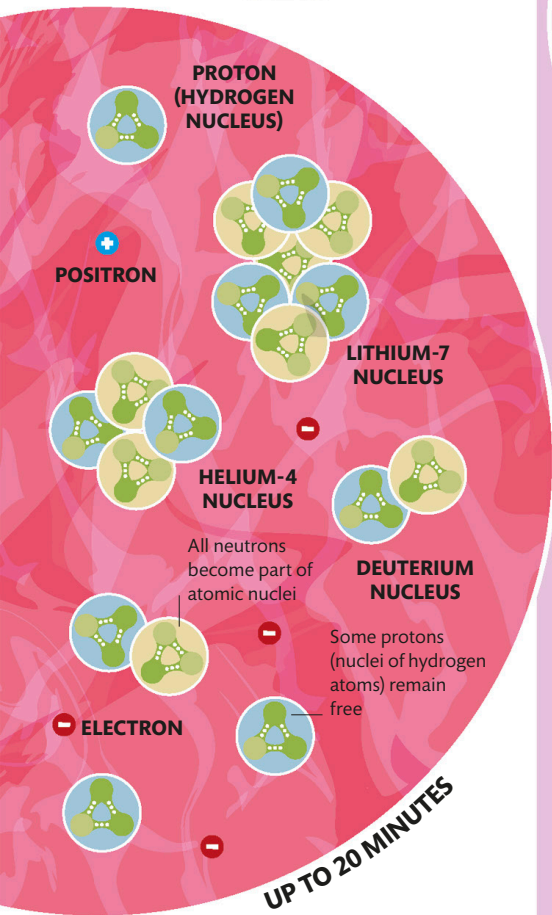
1 Particles and antiparticles form
The first quarks and antiquarks formed spontaneously from the sea of mass-energy during a fleeting period called the quark epoch. The first electrons and positrons also emerged in a process known as leptogenesis.

2 Composite particles form
Quarks were bound together by gluons, which carry the strong nuclear force, to form protons and neutrons, which are both types of composite particle. A proton has an overall positive electrical charge; neutrons have no charge.



WHAT HAPPENED TO ALL THE ANTIMATTER?

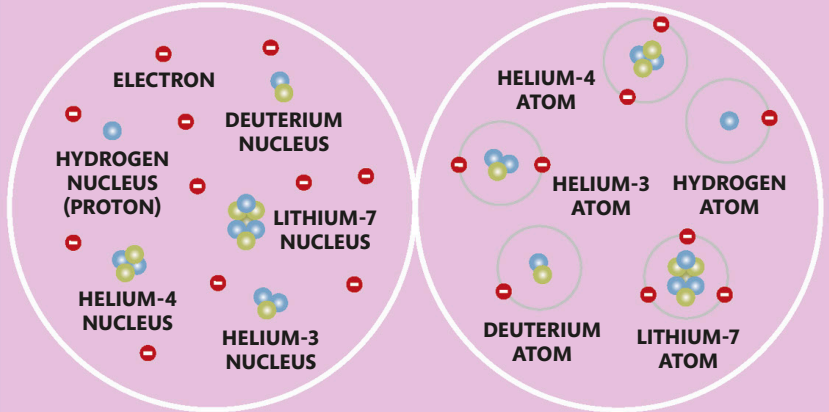
Matter and antimatter were created in almost equal amounts, yet everything we see today is made entirely of matter. An unknown cause must have tipped the balance in favour of matter.



3 Nuclei form
Hydrogen nuclei were present in the form of single protons. Collisions between protons and neutrons formed the nuclei of helium-4 and small amounts helium-3, deuterium, and lithium-7 nuclei.

The first atoms

An atom comprises a positively charged nucleus surrounded by one or more negatively charged electrons, held together by the electromagnetic force. The first nuclei formed within minutes of the Big Bang, but it was 380,000 years before the Universe had cooled enough for them to join with electrons in the process of recombination (see p.164) to make atoms of the first three elements.

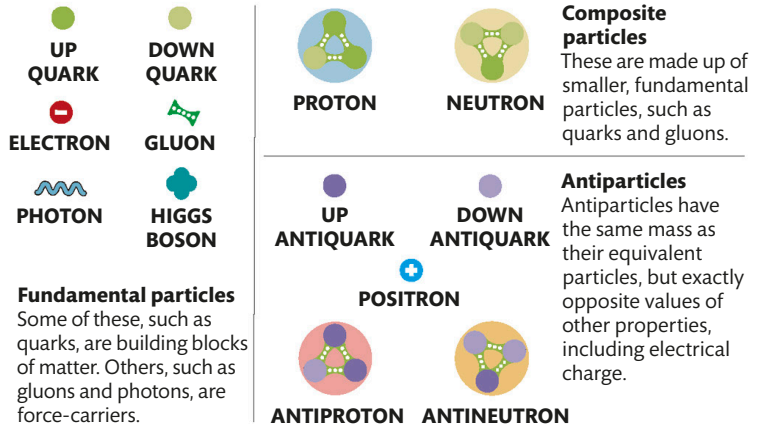


1 Separate nuclei and electrons
For many hundreds of thousands of years, atomic nuclei and electrons existed separately in a hot plasma of fast-moving particles.

2 Atoms form
Eventually, electrons were captured by atomic nuclei to form atoms of helium, hydrogen, deuterium (a heavy form of hydrogen), and lithium.

SUBATOMIC PARTICLES

Atoms are made up of smaller, subatomic particles – protons, neutrons, and electrons. Electrons are fundamental particles, which means they are not made of smaller particles. But protons and neutrons are both made of fundamental particles known as quarks and gluons. Each particle has a corresponding antiparticle.

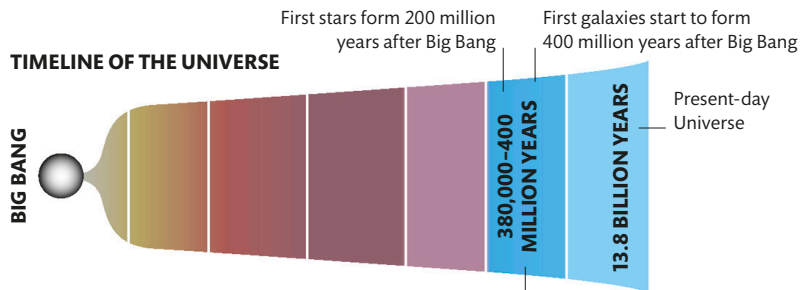


The first stars and galaxies

The first stars started to form only about 200 million years after the Big Bang. The earliest galaxies began to form shortly afterwards as dark matter helped to clump stars together into groups. When these infant galaxies merged, it triggered yet more star formation.

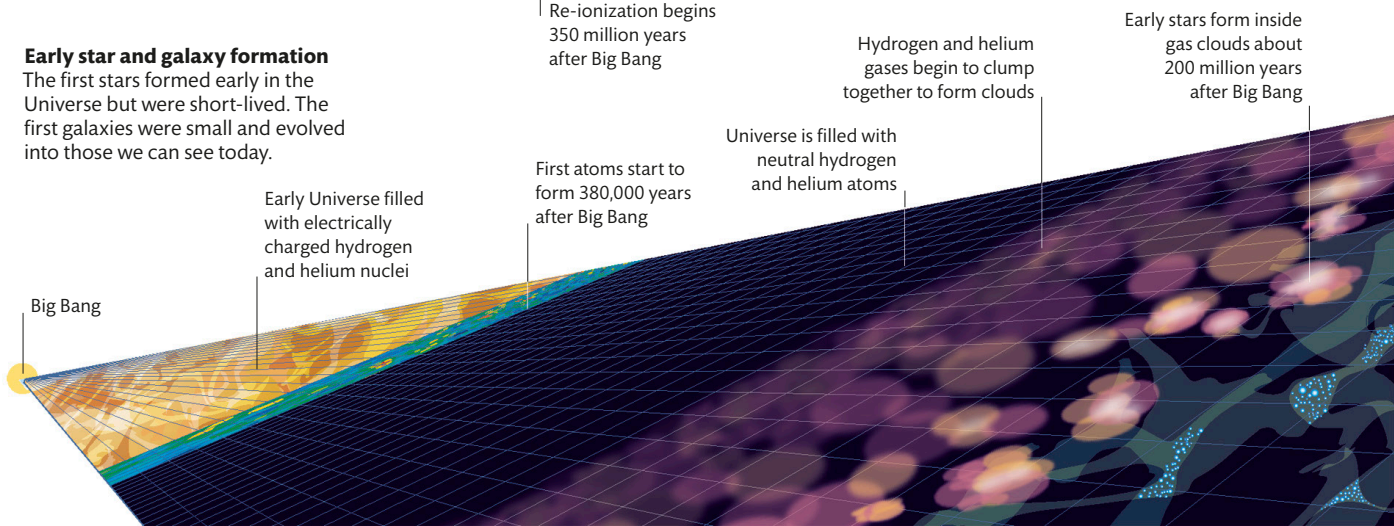
The first stars

Early in the life of the Universe, the only ingredients available for star formation were the hydrogen and helium made shortly after the Big Bang – the first stars contained no heavy elements. These fledgling stars were massive, dozens of times more massive than our own Sun. The intense ultraviolet light they emitted ripped electrons from hydrogen atoms, ionizing the gas between the first dwarf galaxies. The first stars died young, exploding as cataclysmic supernovae within a few million years and creating the first heavy elements.



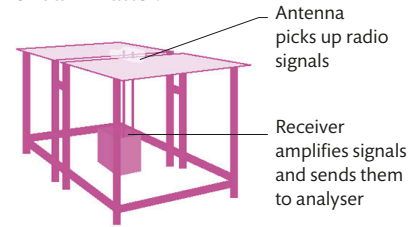
Early star and galaxy formation

The first stars formed early in the Universe but were short-lived. The first galaxies were small and evolved into those we can see today.



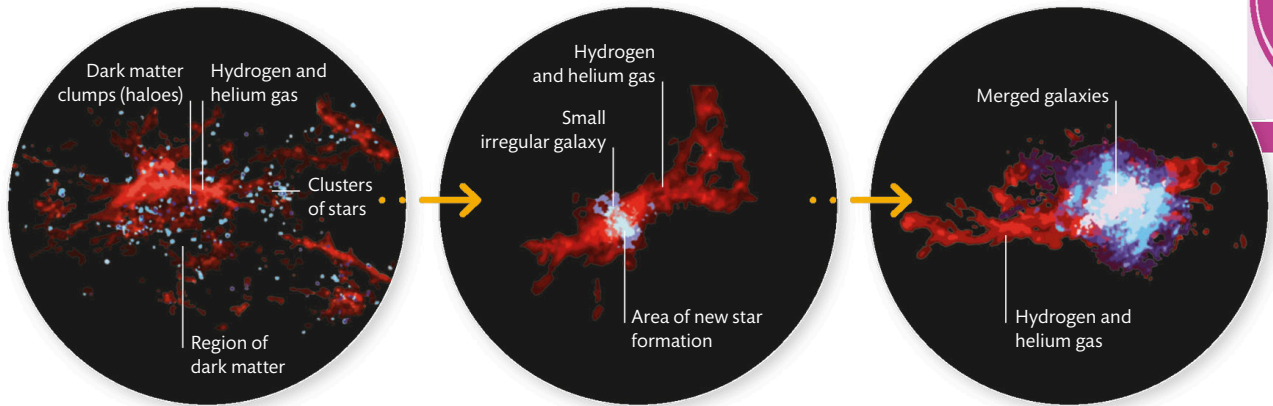
THE EDGES EXPERIMENT

The EDGES experiment uses a special, table-sized type of radio telescope to detect relic radiation from the period of re-ionization (about 350 million to 1 billion years after the Big Bang). Initial results indicate that stars formed early in the life of the Universe and that the cosmos was colder than previously thought, possibly due to the influence of dark matter.



DID THE FIRST STARS HAVE PLANETS?

The first stars may have had planets, but they would not have been rocky, because the early Universe consisted only of gas and hot plasma (a "soup" of electrically charged particles).



1 Dark matter clumps together
Gravitational attraction pulls dark matter together into clumps called haloes. These haloes attract normal matter, such as hydrogen and helium gas, which become compressed further.

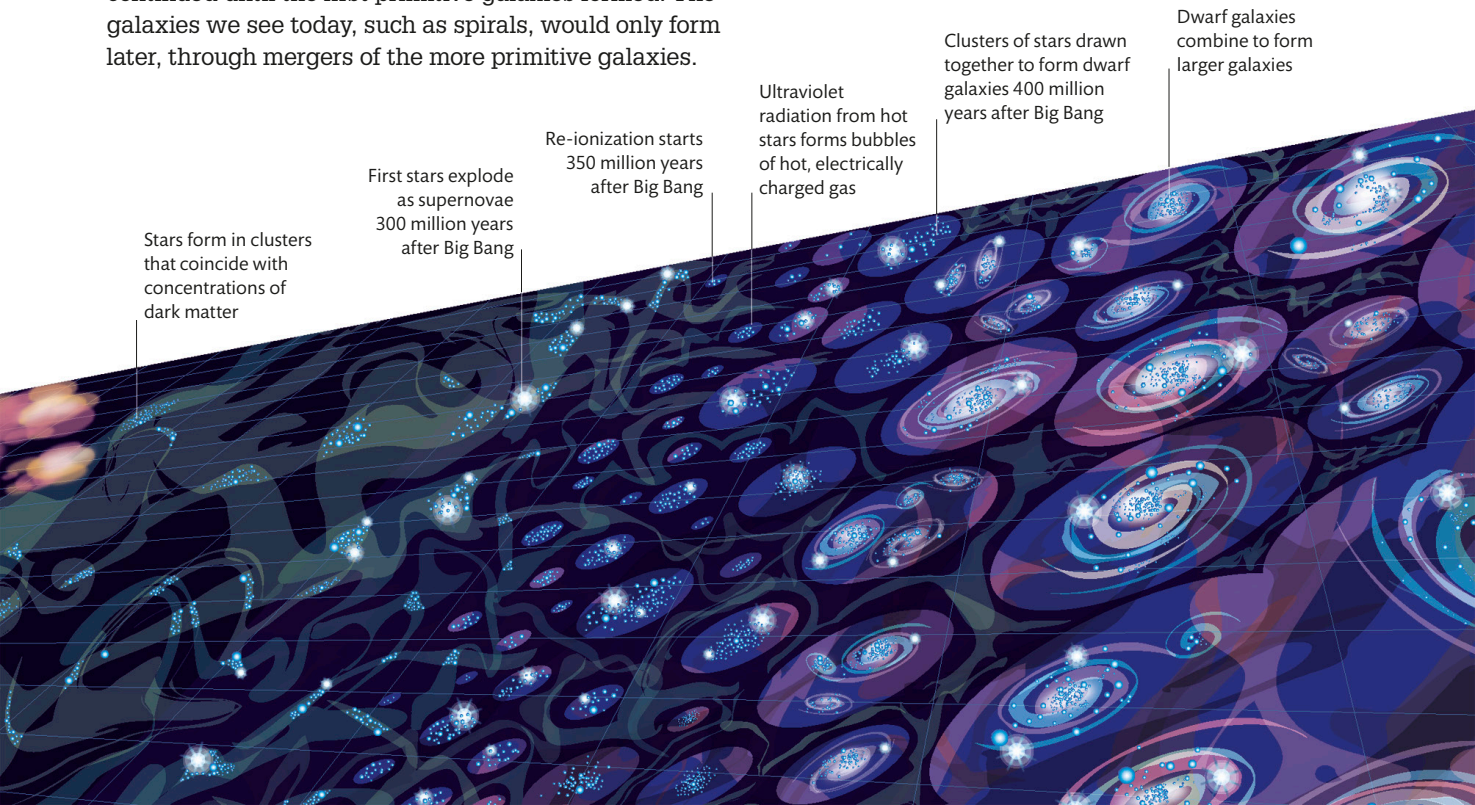
2 Small galaxies form
Matter continues to clump together, eventually forming small irregular galaxies. Inside these galaxies, knots of denser matter develop, creating regions where new stars can start to form.

3 Galaxies merge
The galaxies, which are mostly empty space, thread through each other, creating larger galaxies and even more areas for star formation. Every major galaxy in today's Universe has undergone at least one merger.

The birth of galaxies

The processes by which the first galaxies formed are still uncertain. However, it is thought that, in the early life of the Universe, some regions of space were slightly denser than others. These denser regions attracted dark matter, which, in turn, pulled in gas and stars. This process continued until the first primitive galaxies formed. The galaxies we see today, such as spirals, would only form later, through mergers of the more primitive galaxies.

 **OUR MILKY WAY IS ABOUT 100,000 TIMES MORE MASSIVE THAN THE FIRST GALAXIES**

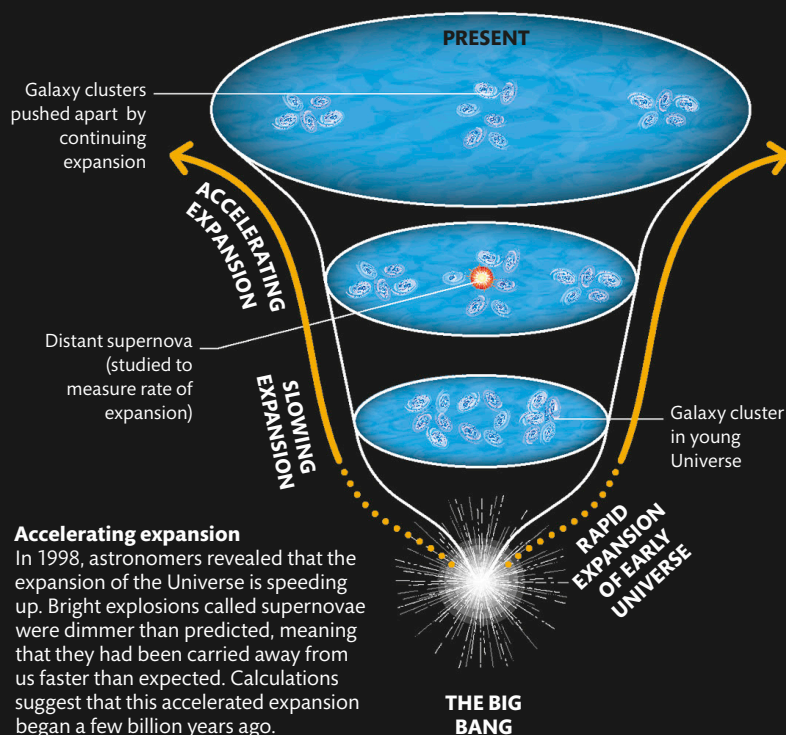


The future of the Universe

What lies in store for our cosmos depends on a battle that has been taking place since the Big Bang between gravity and a little-understood form of energy. Astronomers are still unsure of the outcome.

Dark energy

Astronomers suspect that empty space is full of a mysterious substance or force called dark energy that acts in opposition to gravity. There is always the same amount of dark energy in any given volume of space, so its potency grows as the Universe expands and space swells to a larger volume. This might explain why the expansion of the Universe is accelerating.



Accelerating expansion

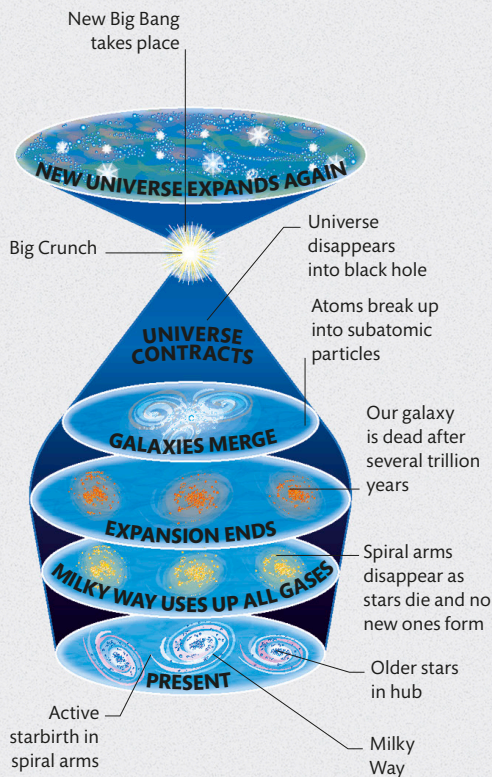
In 1998, astronomers revealed that the expansion of the Universe is speeding up. Bright explosions called supernovae were dimmer than predicted, meaning that they had been carried away from us faster than expected. Calculations suggest that this accelerated expansion began a few billion years ago.

IN THE DISTANT FUTURE, THE UNIVERSE COULD BE COLD AND DEAD OR EVEN RIPPED APART



Possible futures

What will ultimately happen to space depends on whether the gravitational attraction between stars, galaxies, and clusters of galaxies can be overcome by dark energy. If it cannot, the Universe will collapse in on itself in a reversal of the Big Bang. Should gravity be overwhelmed, the Universe will continue expanding, potentially at a catastrophic rate. Alternatively, a new theory in physics could change all our ideas about the potential outcome.



The Big Crunch

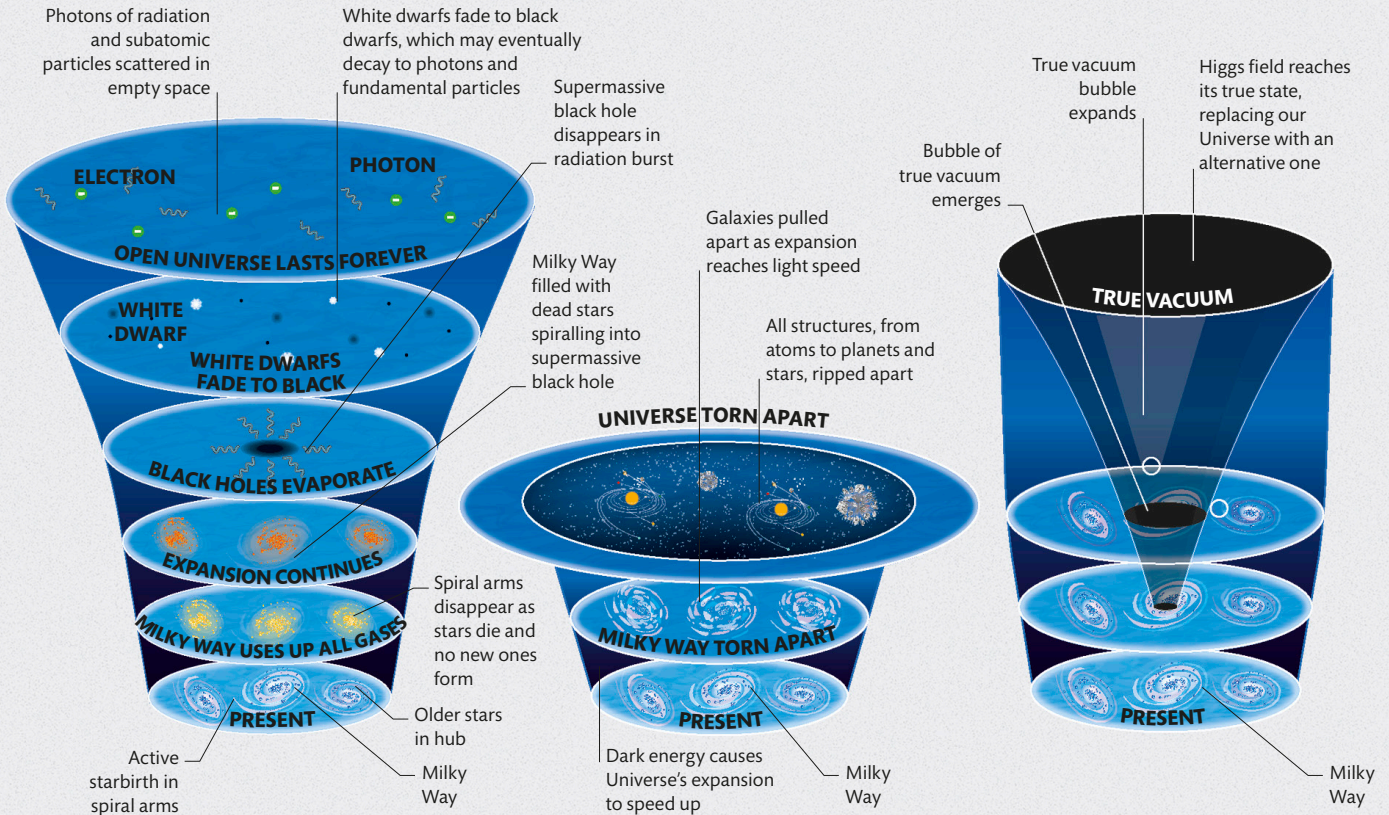
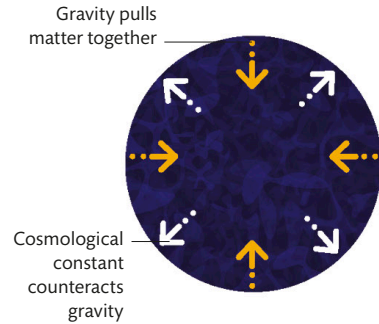
This scenario would see gravity win out. The Universe would become smaller and hotter, eventually shrinking back down to a tiny speck – possibly to be followed by a new Big Bang. This was once a popular idea but has fallen from favour with the discovery of dark energy.

HOW MUCH LONGER WILL THE UNIVERSE LAST?

According to most likely scenarios, the Universe will last for billions of years and might even last for ever. However, it is theoretically possible that it could end at any time if the Big Change model is correct.

THE COSMOLOGICAL CONSTANT

The cosmological constant was introduced by Albert Einstein as an "anti-gravity" force to counterbalance the attractive force of gravity. The discovery that the expansion of the Universe is speeding up seems to imply that the cosmological constant is similar to dark energy, which tends to accelerate expansion.



The Big Chill

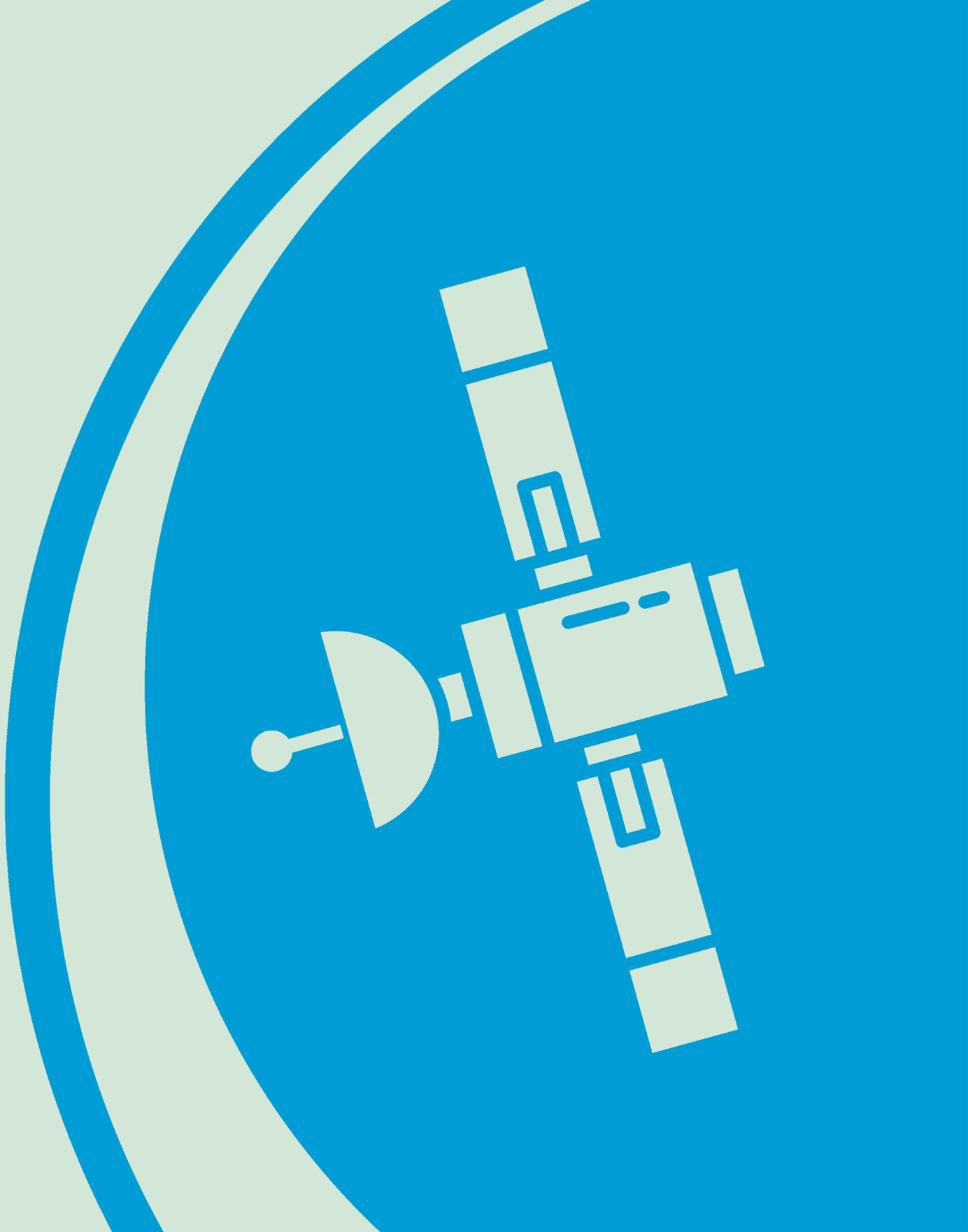
If the Universe continues to expand steadily, then eventually energy and matter will become so diluted that there will not be any planets, stars, or galaxies left. Temperatures will fall to absolute zero, and a sea of atomic shrapnel will be all that is left.

The Big Rip

If dark energy continues to accelerate the expansion of the Universe, after 22 billion years or so all structures, including black holes, will be ripped apart. Even the spaces between atoms and subatomic particles will have stretched so far that they are torn apart.

The Big Change

This theory involves the Higgs boson particle and an energy field called the Higgs field. If the Higgs field reaches its lowest energy, or vacuum state, a bubble of vacuum energy could appear and expand at close to light speed, destroying everything in its path.



SPACE

EXPLORATION

Getting into space

Beyond the protective layers of Earth's atmosphere lies the vastness of outer space. The first hurdle to overcome when exploring space is simply reaching it. Overpowering the pull of Earth's gravity and achieving sufficient speed to enter a stable path around Earth, called an orbit, is the initial challenge. In order to explore interplanetary space beyond Earth's orbit, a further boost of speed and thrust is required.



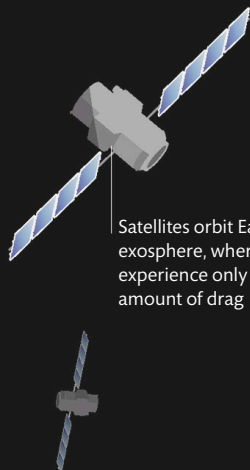
A GERMAN V-2 ROCKET BECAME THE FIRST OBJECT MADE BY HUMANS TO REACH SPACE, IN 1942

Where is space?

As Earth's atmosphere gets thinner at higher altitudes, aircraft find it harder to generate lift using the pressure of air flowing under their wings. Without the molecules contained within an atmosphere to reflect or scatter light, space appears black to our perception. Outer space is generally agreed to be the region where a vehicle must enter orbit around Earth in order to remain above the surface, but there is no officially agreed definition for the "edge of space". US space agency NASA puts the beginning of space at 80km (50 miles) above sea level, while the International Aeronautical Federation (FAI) puts it at 100km (60 miles).

Exosphere

In the outermost layer of the atmosphere, beginning about 600 km (370 miles) above the surface, air pressure no longer falls with increasing altitude. The exosphere's sparse gases merge gradually into space.

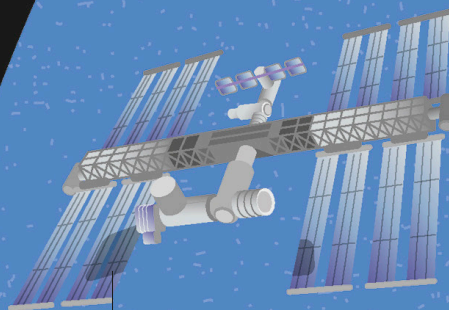


Satellites orbit Earth in exosphere, where they experience only a small amount of drag

EXOSPHERE (600+ KM / 370+ MILES)

THERMOSPHERE (600 KM / 370 MILES)

Aurorae occur at varying altitudes, mostly in thermosphere

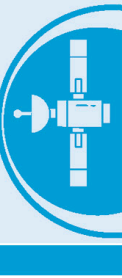


Low-orbiting spacecraft and space stations orbit in thermosphere

Thermosphere

Above about 85 km (53 miles), ultraviolet radiation breaks gas molecules apart into electrically charged ions, creating a layer of hot but tenuous gas called the thermosphere. Aurorae are mostly formed in this layer.

MESOSPHERE



HAS ANYONE EVER REACHED SPACE IN AN AEROPLANE?

Yes. In the 1960s, eight US pilots reached the edge of space in a hypersonic, rocket-boosted plane called the X-15, dropped by a large carrier aircraft.

Mesosphere

Above about 50–65 km (30–40 miles), atmospheric temperatures fall again within a layer called the mesosphere. This layer is too high for conventional aircraft to reach, but too low for spaceflight.

(85 KM / 53 MILES)

Most shooting stars burn up in mesosphere

Highest weather balloons reach lower mesosphere

Commercial airliners cruise troposphere

STRATOSPHERE (50 KM / 30 MILES)

TROPOSPHERE (6–20 KM / 4–12 MILES)

Stratosphere

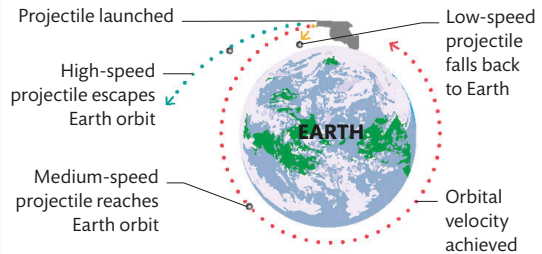
While temperatures fall with increasing altitude in the troposphere, they increase with altitude through the stratosphere, where gases including ozone absorb the Sun's ultraviolet rays.

Troposphere

The lowest layer of Earth's atmosphere contains 75 per cent of its mass and 99 per cent of all its water vapour. It extends to around 20 km (12 miles) above the equator but just 6 km (4 miles) above the poles.

ESCAPING EARTH'S GRAVITY

In order to completely escape Earth's pull, a vehicle must reach a speed known as escape velocity, where it is travelling so fast that Earth's gravity can never fully slow it down. Escape velocity at Earth's surface is approximately 11.2 km (7.0 miles) per second, which is far greater than the speed required to achieve orbit.

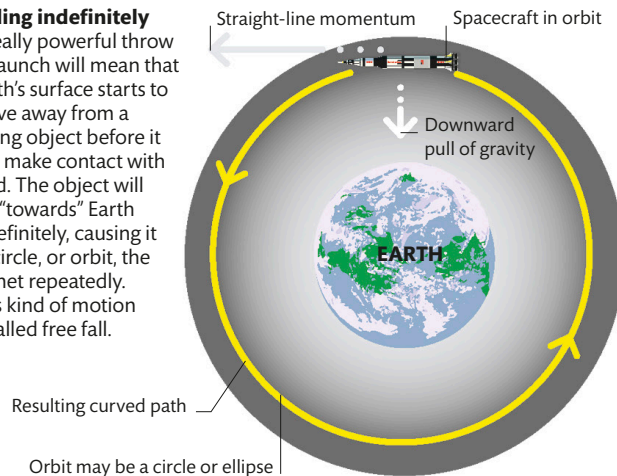


Reaching orbit

In order to remain in space and not fall back to Earth, any vehicle must achieve a stable orbit – a circular or elliptical loop around Earth at sufficient height for it to avoid being slowed too much by drag from the upper atmosphere. An orbit is a path on which an object's momentum (which gives it a tendency to continue moving in a straight line) is exactly countered by the pull of gravity towards Earth. For a circular low Earth orbit (LEO) 200 km (125 miles) above the surface, this requires a spacecraft or space station to reach a speed of 28,000 km (17,400 miles) per hour.

Falling indefinitely

A really powerful throw or launch will mean that Earth's surface starts to curve away from a falling object before it can make contact with land. The object will fall "towards" Earth indefinitely, causing it to circle, or orbit, the planet repeatedly. This kind of motion is called free fall.



Rockets

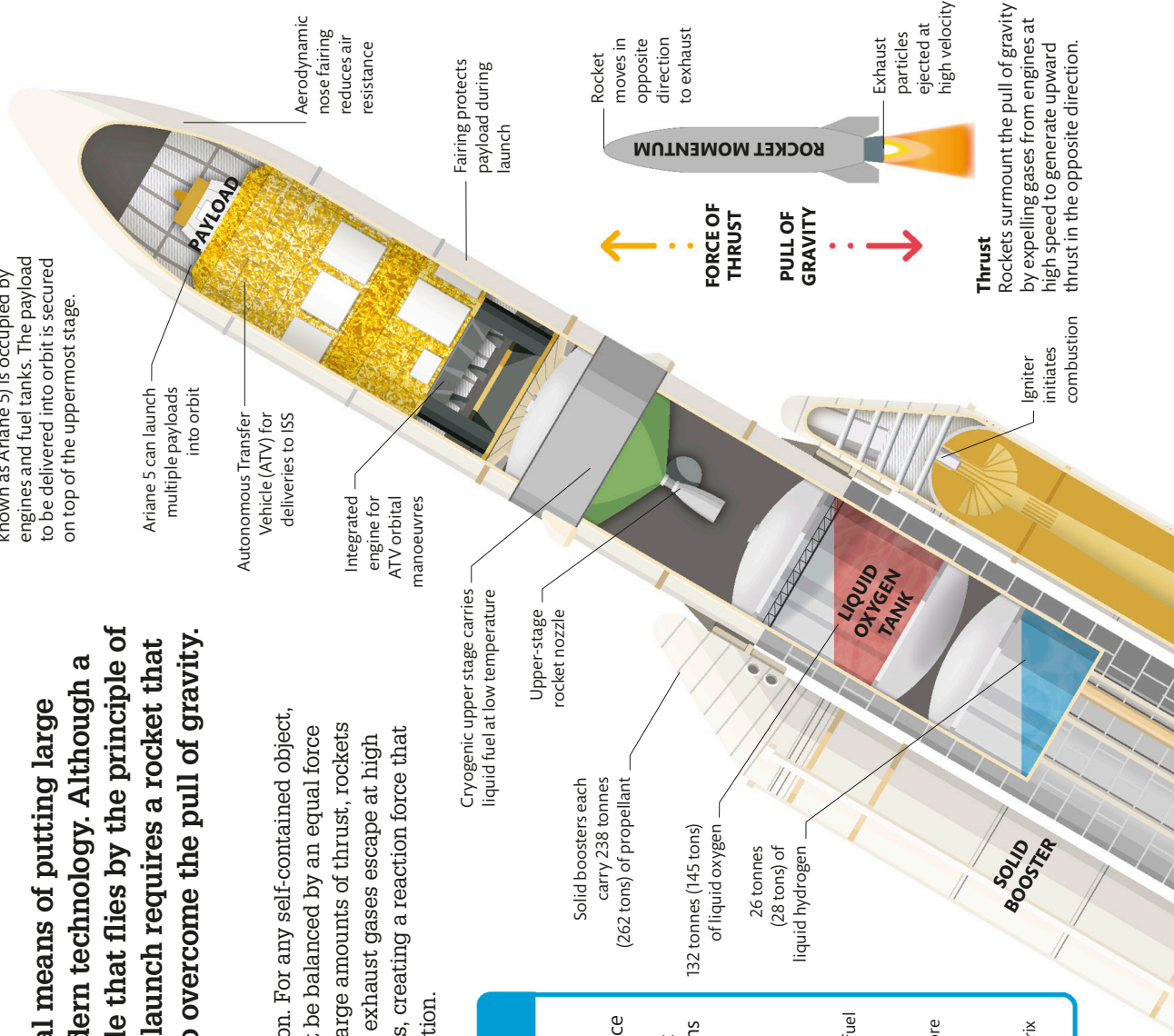
Rockets are the only practical means of putting large objects into space using modern technology. Although a rocket is simply any projectile that flies by the principle of action and reaction, a space launch requires a rocket that generates sufficient thrust to overcome the pull of gravity.

How rockets work

Rockets are based on action and reaction. For any self-contained object, a force generated in one direction must be balanced by an equal force in the opposite direction. To generate large amounts of thrust, rockets burn chemicals called propellants. The exhaust gases escape at high speed through specially shaped nozzles, creating a reaction force that pushes the rocket in the opposite direction.

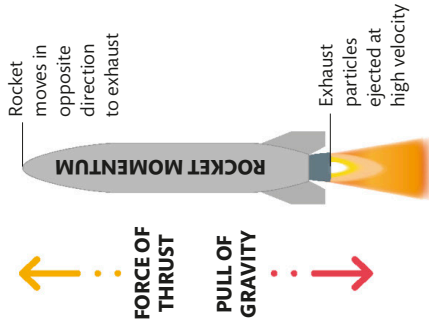
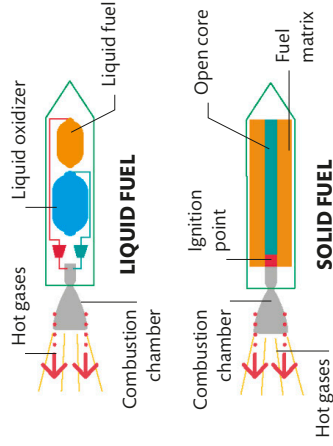
Inside a liquid-fuelled rocket

At launch, the bulk of a rocket, (such as this European Space Agency rocket known as Ariane 5) is occupied by engines and fuel tanks. The payload to be delivered into orbit is secured on top of the uppermost stage.



ROCKET PROPELLANTS

Rockets burn propellants to generate explosive thrust. Most combine two liquid chemicals, a fuel and an oxidizer, to produce a chemical reaction. Solid-fuelled rockets are much easier to manufacture. They mix both chemicals in a solid "matrix" that burns continually once ignited within a cylinder.

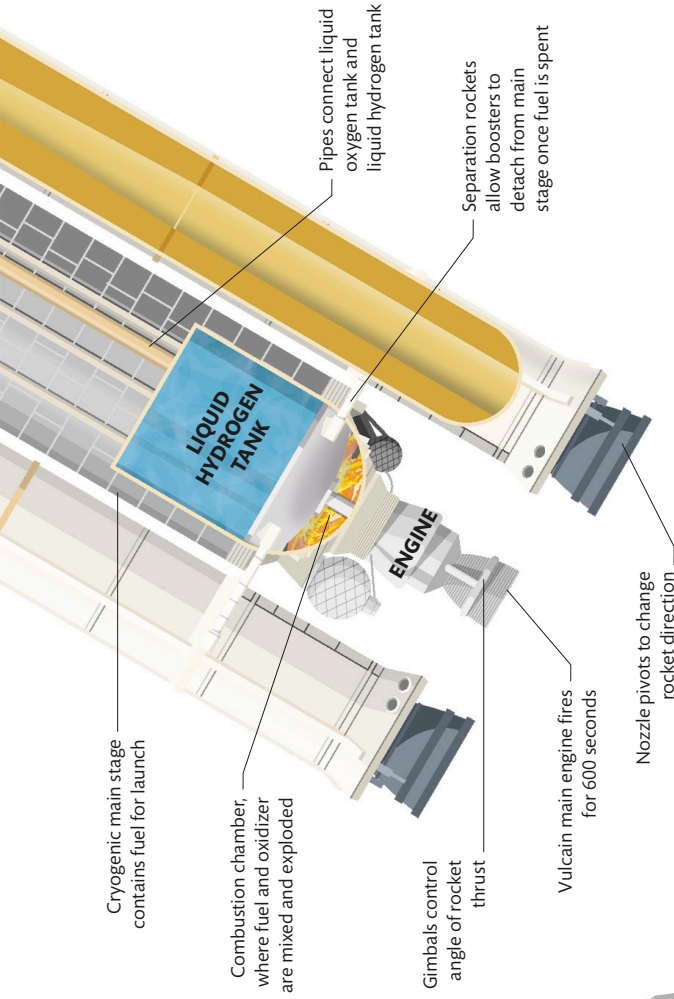


Thrust
Rockets surmount the pull of gravity by expelling gases from engines at high speed to generate upward thrust in the opposite direction.



WHO INVENTED THE SPACE ROCKET?

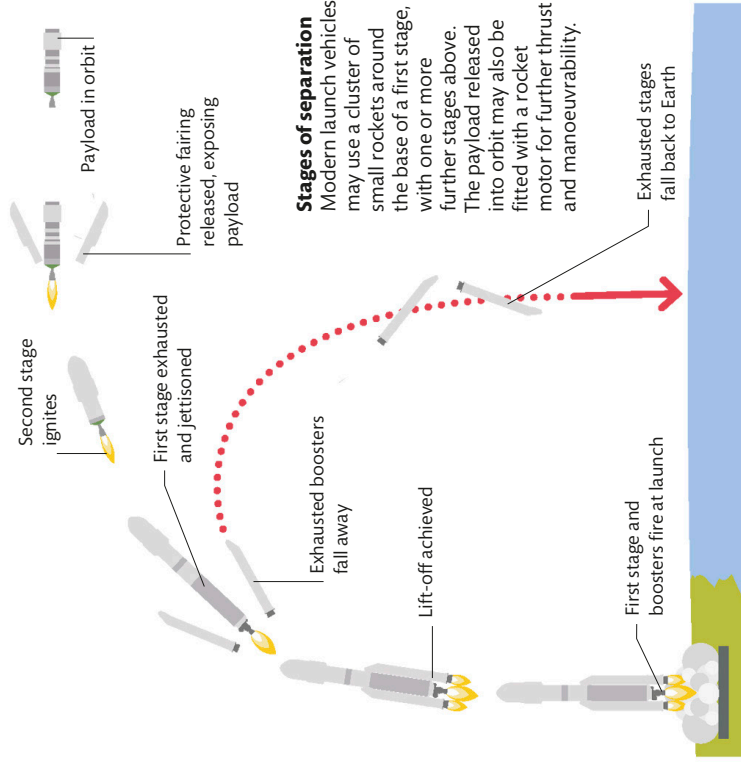
The first person to seriously propose using rockets for space travel was Russian teacher, physicist, inventor, and aviation engineer Konstantin Tsiolkovsky (1857–1935).



NASA'S GIANT SATURN V MOON ROCKET DELIVERED JUST 4 PER CENT OF ITS LAUNCH WEIGHT INTO EARTH ORBIT

Multi-stage rockets

Although the action and reaction forces generated in a rocket are equal, they produce a far greater acceleration in the escaping lightweight exhaust gas than they do on the mass of the rocket itself. Because the rocket must move from the outset with enough thrust to overcome gravity (to avoid falling back to Earth), it must therefore burn huge amounts of fuel in the first few moments after launch. In order to reduce the amount of excess mass carried into orbit, many rockets consist of several stages with separate fuel tanks and engines that are fired either in sequence or in parallel, and then jettisoned as the rocket gains speed and their fuel is exhausted.



Stages of separation

Modern launch vehicles may use a cluster of small rockets around the base of a first stage, with one or more further stages above. The payload released into orbit may also be fitted with a rocket motor for further thrust and manoeuvrability.

Reusable rockets

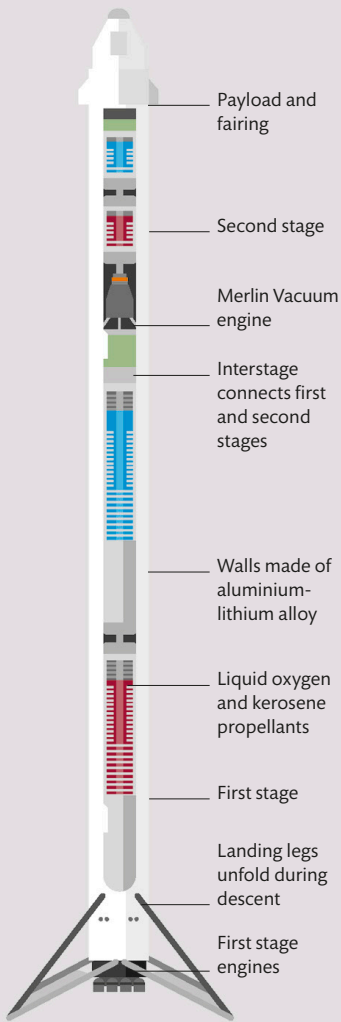
Traditional rockets are expensive and wasteful – not only do they burn huge amounts of fuel, but the fuel tanks and engines are also discarded and unsalvageable, despite being used on just a single flight. Developing fully reusable rockets is essential to lower the cost of access to space.

Return and recycle

Since 2015, US company SpaceX has pioneered the successful landing and reuse of rocket stages from its Falcon launch vehicles. The lower stages (either single rockets or clusters of three) are equipped with steering thrusters that guide them back to a pre-planned landing site (either on land or on a floating platform at sea). They are jettisoned from the upper stage with excess fuel still on board to slow their descent during final approach.

WHAT WAS THE FIRST PARTIALLY REUSABLE SPACE VEHICLE?

The Space Shuttle, launched for the first time in 1981, featured a reusable orbiter and solid rocket boosters that could be refurbished.



Landing a rocket

With an 85 per cent success rate, Falcon 9 has made the incredibly difficult task of bringing a rocket stage back to a vertical landing look deceptively simple. However, landing a rocket under power, on target, and in good condition for reuse involves some ingenious new technology.

1 Lift-off!

Falcon 9 launches vertically like any traditional rocket. The "Full Thrust" version of the rocket stands 70m (230ft) tall on the launchpad and consists of two stages, an interstage, and the payload with its fairing on top.

2 First-stage burn

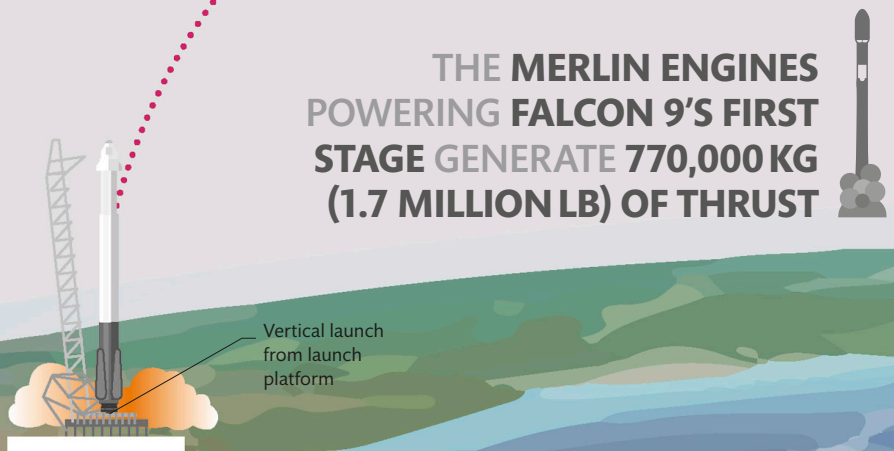
At launch, nine Merlin engines on the rocket's first stage ignite. Arranged in a configuration known as an "octaweb", they burn a mix of RP-1 (a kerosene-based rocket fuel) and liquid oxygen.

Main engine cut-off precedes stage separation

3 Engine cut-off

The first-stage rocket engines cut out after around 180 seconds, having carried the vehicle to altitudes of around 70 km (44 miles) and speeds of around 7,000 kph (4,400 mph).

THE MERLIN ENGINES POWERING FALCON 9'S FIRST STAGE GENERATE 770,000 KG (1.7 MILLION LB) OF THRUST



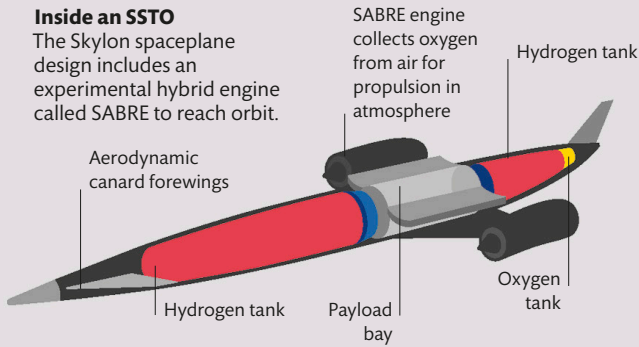


Single-stage-to-orbit vehicles

The ideal means of reaching orbit is with a single-stage-to-orbit (SSTO) vehicle that can reach space in one piece and return to Earth for a rapid turnaround. SSTO concepts include traditional vertically launched rockets, but also spaceplanes fitted with efficient hybrid engines to deliver a payload to low Earth orbit.

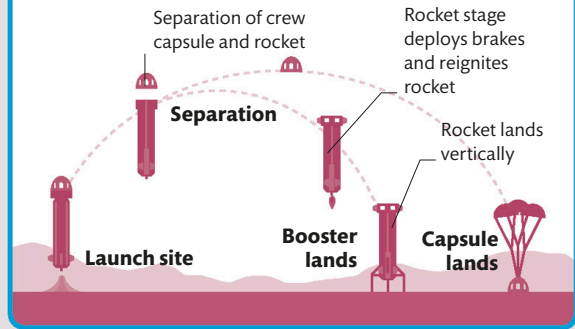
Inside an SSTO

The Skylon spaceplane design includes an experimental hybrid engine called SABRE to reach orbit.



SUBORBITAL FLIGHT

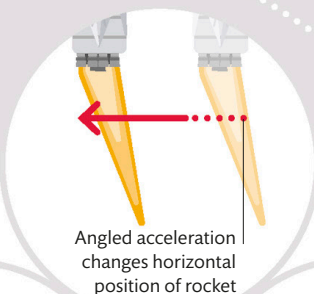
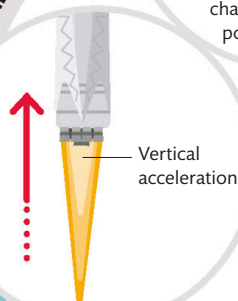
Blue Origin's New Shepard rocket is a vertical take-off SSTO intended to launch a passenger capsule for short flights that reach space but do not enter orbit. In November 2015, an uncrewed New Shepard was the first vertical rocket to reach space and make a return to Earth.



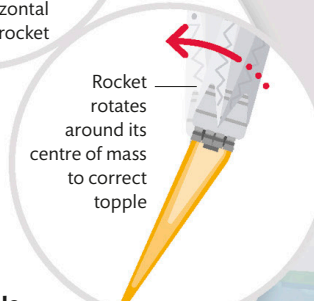
4 Separation

Pneumatic pistons in the interstage unit push the two rocket stages away from each other. As the first stage falls back towards Earth, gas thrusters turn it so that it falls base first.

LANDING VERTICALLY



Angled acceleration changes horizontal position of rocket



Rocket rotates around its centre of mass to correct topple

Variable acceleration

By altering the angle of thrust from its engines, Falcon 9 can change direction as it descends in order to land vertically.

5

Payload delivered

A single-engined second stage delivers the payload (such as a crew capsule bound for the ISS) to low Earth orbit or a geostationary transfer orbit. The second stage is not recovered after use.

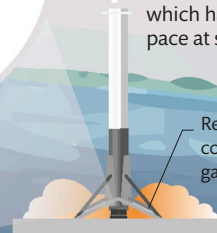
Engines reignite to slow descent

6

Touchdown

The first stage reignites three Merlin engines to slow its descent. Asymmetrical landing legs extend just prior to landing and cushion the touchdown, which happens at walking pace at sea or on land.

Release of compressed helium gas cushions landing



Satellite orbits

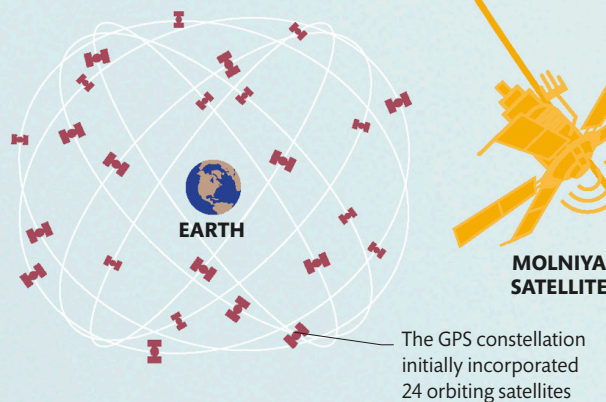
A satellite's orbit is a stable circular or elliptical path around an object taken under the influence of gravity. Satellites follow a variety of orbits around Earth depending on their purpose.

Types of orbit

A satellite's speed relative to Earth's surface varies with its altitude. Those in circular orbits maintain a constant speed, with those in low orbits moving faster than those in high orbits. Elliptical orbits cause a satellite to move relatively fast at perigee (when it is closest to Earth) and slower at apogee (when it is furthest away). While some satellites orbit directly above the equator, most are inclined (tilted at an angle), so they pass over different points on the surface as Earth rotates beneath them.

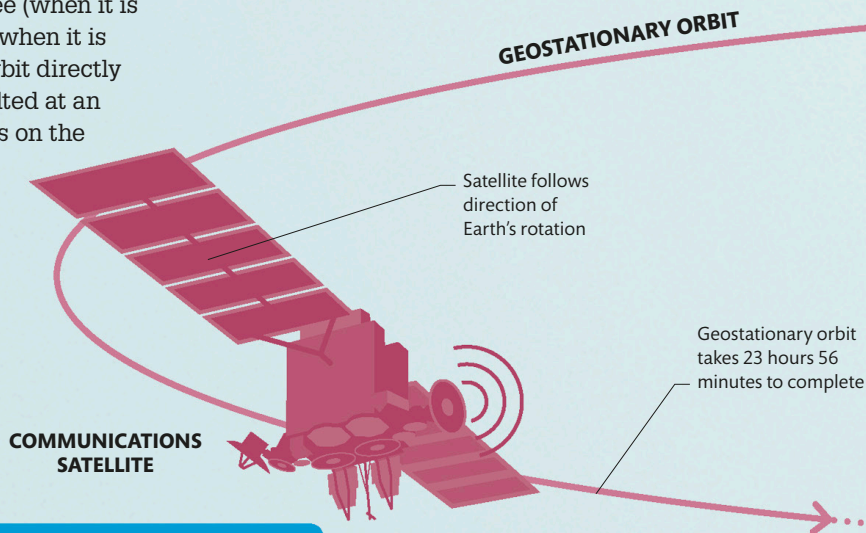
Classifying orbits

Low Earth orbits, near-circular paths in the thermosphere, are the most easily reached. Earth-observing satellites in polar orbits fly over a different band of Earth's surface on each orbit. Sun-synchronous orbits allow satellites to compare strips of Earth's surface under even lighting. Elliptical and high orbits take them much further away from Earth, bringing more surface into view.



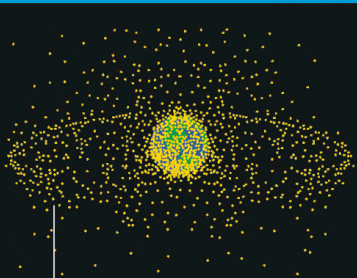
Satellite constellations

Applications such as satellite telephony and navigation require multiple satellites to work together in a group known as a constellation. The satellites fly in precisely arranged low- or mid-altitude Earth orbits to provide continuous coverage of Earth's surface.



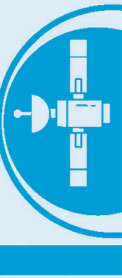
SPACE JUNK

Since the beginning of the space age in 1957, space around Earth has become increasingly crowded, not only with working satellites but also with redundant spacecraft, used rocket stages, and other debris. Collisions are a constant danger to working satellites, crewed spacecraft, and even the International Space Station and the personnel aboard.



WHAT WAS THE FIRST SATELLITE ORBIT?

Sputnik's orbit ranged from 215 to 939 km (133 to 583 miles) above the Earth, and was tilted at 65° to the equator.



Orbital manoeuvres

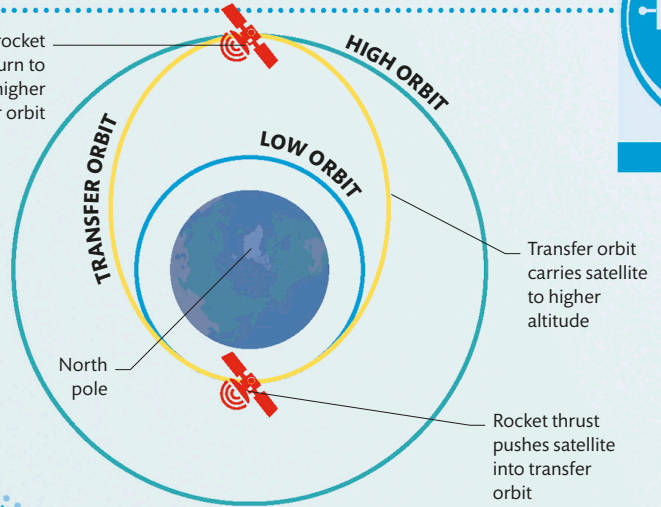
Most satellites are initially launched into low Earth orbit (LEO). From here, they use onboard engines and rocket thrusters, or a final upper-stage rocket motor, to reach their final desired orbit.

Changing the shape and size of orbit is far easier than altering its inclination once in space.

Transfer orbits

Satellites can move between circular orbits along paths called transfer orbits. A transfer orbit is a segment of an elliptical orbit that touches the lower circle at perigee and the upper circle at apogee. A precise engine burn is required at each stage.

Second rocket burn to enter higher circular orbit



Satellite uses

The majority of satellites are designed to do specific tasks that relate to Earth. Following the right type of orbit is a vital element of getting the job done.



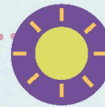
Satellite telephony

Satellite phone services are provided by constellations in LEOs. Several satellites are within range from any point on Earth at one moment.



Earth mapping

Sun-synchronous orbits ensure that space-based photographs of Earth's surface are all illuminated from the same direction.



Earth monitoring

Satellites designed to track various aspects of Earth's climate follow polar orbits. They can build up a complete picture of conditions on Earth.



Broadcasting

Many broadcasting satellites follow geostationary orbits over the equator, where they orbit in the same period as Earth rotates.



High latitudes

For high-latitude areas where equatorial comsats may be out of sight, satellites follow highly inclined, highly elliptical orbits, called Molniya orbits.



ACCORDING TO A RECENT COUNT
THERE ARE 129 MILLION OBJECTS
LARGER THAN 1 MM (0.04 IN) IN
ORBIT AROUND THE EARTH



Solar panels generate electricity to power satellite

Anatomy of a comsat

Communications satellites (comsats) feature extremely sophisticated equipment designed to cope for extended periods of time in the extreme conditions of space, where maintenance is practically impossible. Power is generated by solar panels.

Communications satellites

Many satellites act as relays for radio signals used in various types of communication. A satellite high above Earth can maintain a direct line of sight to receivers and transmitters on the ground below, allowing access to communications such as telephone, internet services, and satellite television even in remote areas beyond the range of ground-based radio transmitters. Satellites in geostationary orbit 35,786 km (22,236 miles) above Earth can remain stationary above a fixed point on the equator, hanging in the sky and acting as broadcast platforms for signals that can be picked up by receivers across a large expanse of Earth's surface.

WHO INVENTED THE COMSAT?

The idea of a communications relay in geostationary orbit was proposed by science fiction author Arthur C. Clarke in 1948 – although he thought such a relay would have to be a crewed space station.

Position of satellite controlled by stationary plasma thruster

2

Incoming signal amplified

Satellites boost the original radio signal using power from their solar panels. Onboard technology may be capable of processing many separate signals at once.

Fuel for thrusters stored in pressurized liquid propellant tanks

Reflector receives incoming radio signals and redirects them to antenna feed

Optical solar reflectors control satellite's temperature

Telemetry, tracking, and command antenna allows ground station to monitor and control satellite operations

Incoming radio signals are fed by antenna to transponder for processing; antenna sends outgoing signals back to Earth via reflector

RADIO SIGNALS

3

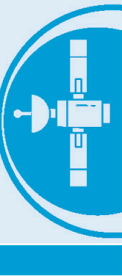
Signal transmitted back to Earth

The satellite retransmits the signal to Earth, either as a narrow beam directed to another ground station, or as a broadcast signal that is weaker and more widely spread.

1

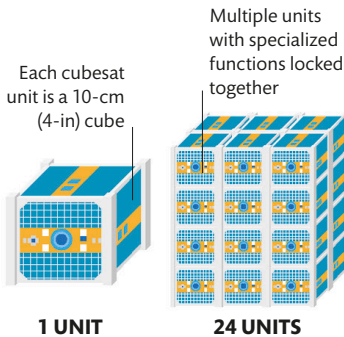
Signal transmitted

Radio signals may be sent to the satellite from a ground station equipped with a powerful, directional dish antenna or from much weaker sources such as the antenna on a satellite phone.



CUBESATS

While geostationary comsats must be large in order to generate enough power for relaying and broadcasting signals over long distances, sending signals to and from low Earth orbit (LEO) takes much less energy. Earth is now orbited by flocks of small comsats in LEO, often designed around an efficient, modular, and lightweight template called the cubesat.



4

Signal received

The receiver may either decode the radio signal, channel it into a ground-based communications network, or retransmit it to another comsat for relaying further around the world.



GROUND
STATION

Types of satellite

Satellites have a wide variety of uses, but the vast majority are involved in communications and navigation, with applications ranging from steering supertankers to broadcasting television.

GPS and navigation satellites

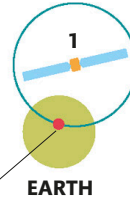
Because radio signals travel at a known speed (the speed of light), it is possible to use time signals received from satellites in well-defined orbits to pin down a receiver's location on Earth. This is the basis of satellite navigation systems such as the Global Positioning System (GPS), which have become an indispensable part of modern technologies ranging from smartphones and cars to crop management.

Satellite 1

A timed signal from a single satellite locates a receiver at a known distance, somewhere on a spherical surface.

Receiver's distance from Satellite 1 is a point on a circle

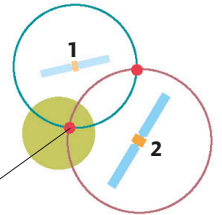
EARTH



Satellite 2

Comparison with a signal from a second satellite reduces the possible location to two intersection points.

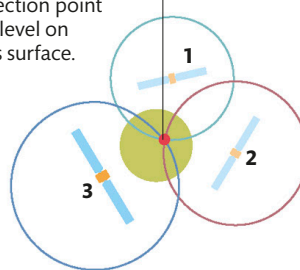
Location narrowed down to either of two points



Satellite 3

A third satellite signal will provide a single intersection point at sea level on Earth's surface.

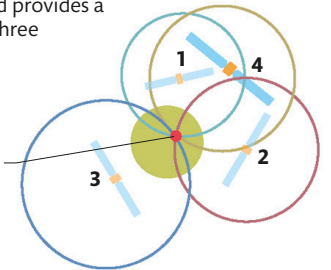
Receiver location can now only be a single point



Satellite 4

A fourth satellite signal takes account of varying altitudes and provides a position in three dimensions.

Position confirmed to within 1 m (3ft)



THE EUROPEAN **GALILEO** SATELLITE NAVIGATION SYSTEM CAN **PINPOINT POSITIONS ON EARTH TO WITHIN 20 CM (8 IN) OR BETTER**



Looking back at Earth

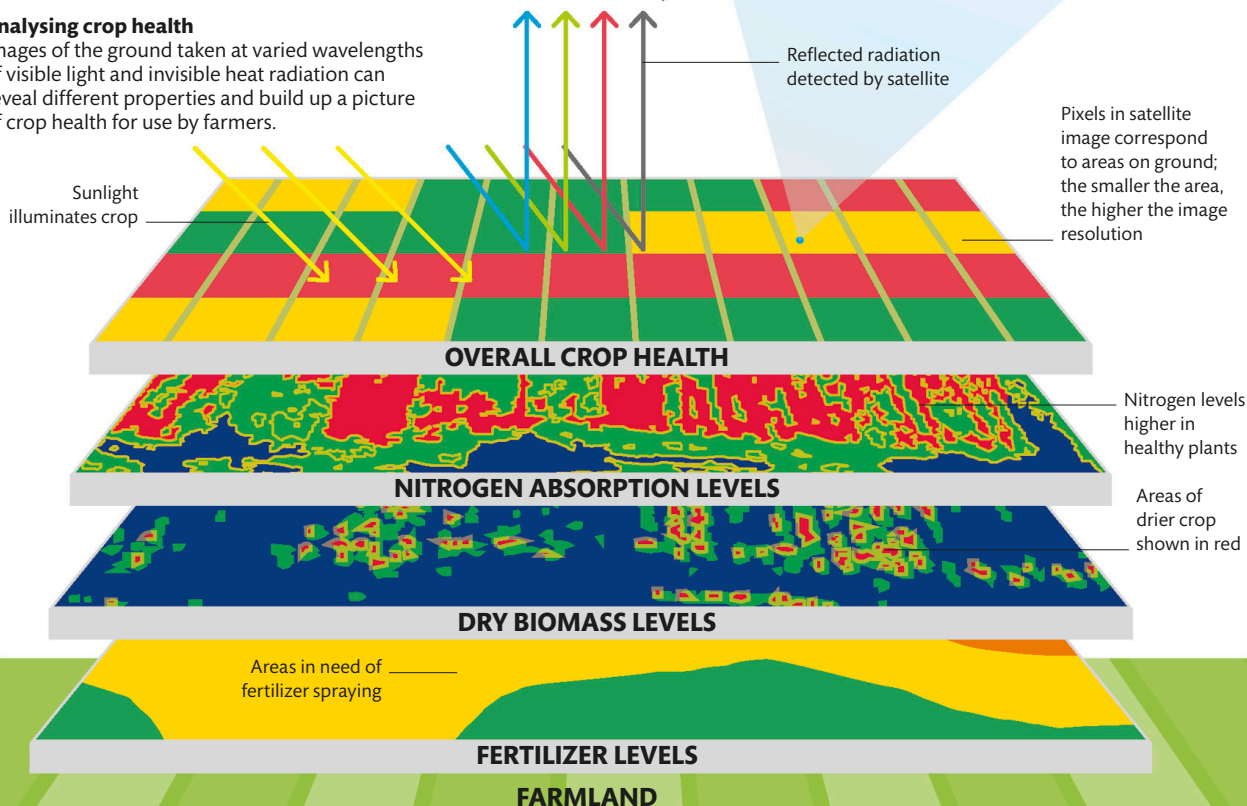
Large numbers of satellites now monitor Earth's land surface, atmosphere, and oceans from space, using a variety of techniques known as remote sensing.

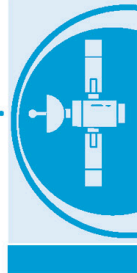
Earth in many wavelengths

The idea of remote sensing began in the 1960s when astronauts reported seeing surprising levels of detail from orbit. The first attempts at studying Earth from space involved simple photography, sometimes enhanced by telescopes. Since then, more advanced tools have been introduced, such as photographing the surface through filters to determine its response to light at specific wavelengths – a technique called multispectral imaging.

Analysing crop health

Images of the ground taken at varied wavelengths of visible light and invisible heat radiation can reveal different properties and build up a picture of crop health for use by farmers.



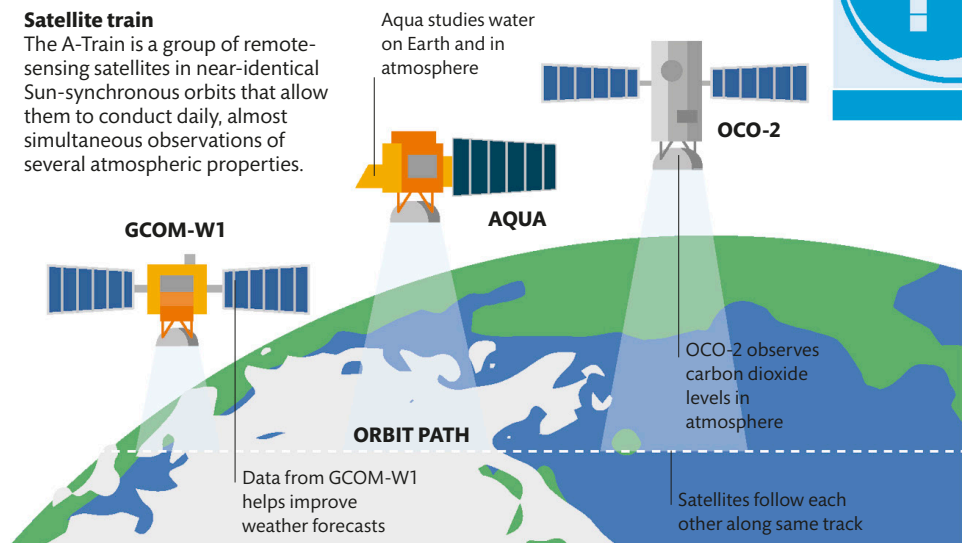


Weather satellites

Weather monitoring was one of the first applications of satellites. Photographing the atmosphere from high orbit allows a more detailed understanding of large-scale weather patterns, while radar systems study the effects of Earth's atmosphere and ocean surface on reflected radio beams in order to measure wind speed, rainfall, and wave heights. Satellites can also detect the levels of pollutants in Earth's atmosphere, and measure the temperature to keep track of climate change.

Satellite train

The A-Train is a group of remote-sensing satellites in near-identical Sun-synchronous orbits that allow them to conduct daily, almost simultaneous observations of several atmospheric properties.



REMOTE-SENSING TECHNOLOGIES

Satellites carry a wide variety of different tools and sensors, including spectrometers that analyse the absorption and reflection of light at different wavelengths, and radar that can map Earth's landscape and oceans.



Meteorology

Photography of cloud patterns can be supplemented by radar measures of wind speed and rainfall, and by infrared cameras that measure surface temperatures.



Oceanography

Radar instruments measure the speed and height of waves, revealing circulation patterns and wind speeds at sea. Infrared detectors can track ocean temperatures.



Geology

Hyperspectral imaging measures the complete spectrum of light reflected from Earth's surface. This can help identify specific rocks and minerals.



Surveying

Satellite-based radar can produce maps of terrain across large areas of the globe, while stereo photography of small areas can be used to create 3D models.



Land use

Multispectral imaging can help distinguish between areas of natural forest, agriculture, urban development, and water, revealing patterns of land use.



Archaeology

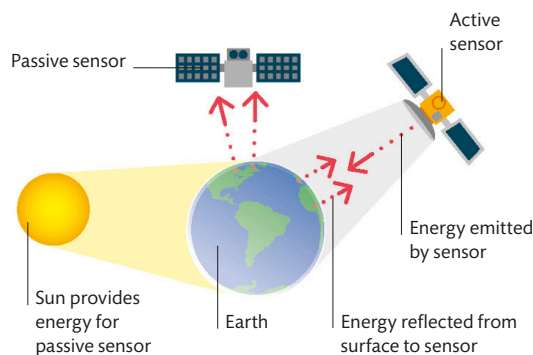
Satellite images and ground-penetrating radar can reveal the outlines and remains of ancient settlements and structures that have become buried over centuries.

IN 2011, 17 PREVIOUSLY UNKNOWN EGYPTIAN PYRAMIDS WERE UNCOVERED USING SATELLITE IMAGERY



ACTIVE AND PASSIVE REMOTE SENSING

Remote sensing systems that measure naturally available energy are called passive sensors. Passive remote-sensing instruments can only be used to detect energy when it is naturally available. Active remote-sensing instruments can fire out signals using their own energy source and analyse the results.



REMOTE SENSING

Looking further into space

Satellite-based astronomical observatories can study the Universe in new ways, capturing perfect images free from turbulence and detecting radiation that is blocked by Earth's atmosphere.

Space telescope orbits

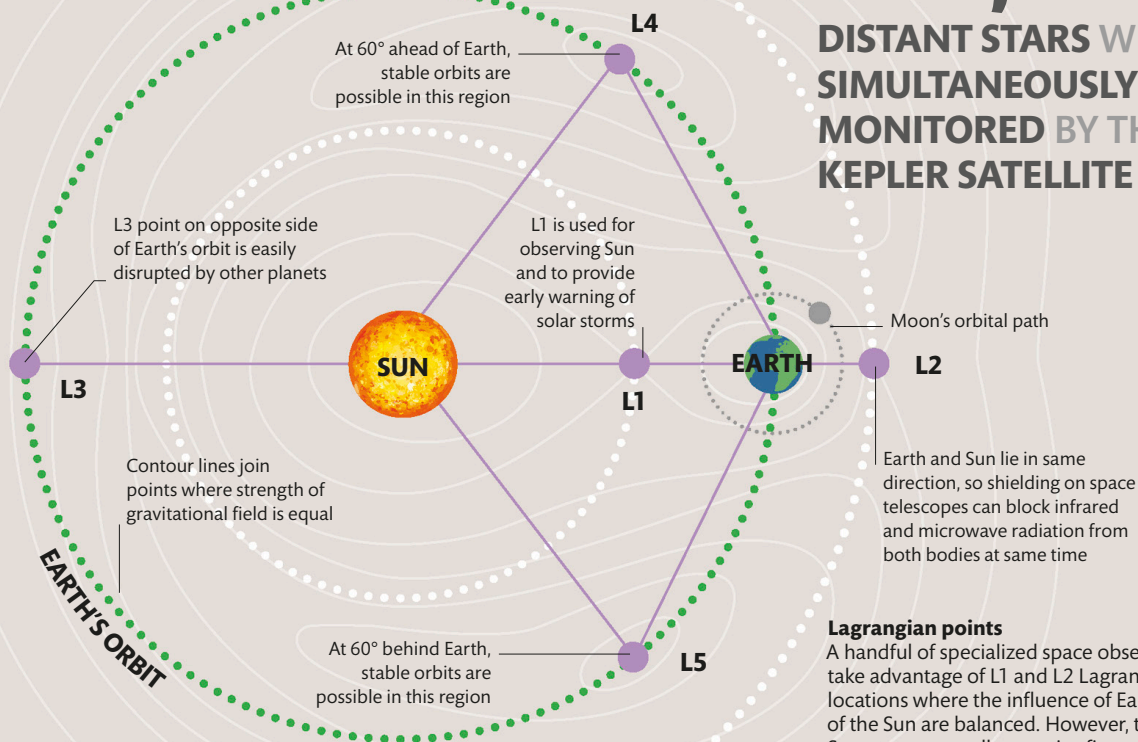
While standard low Earth orbit is sufficient for many space telescopes, some missions require more complex orbits. More distant orbits reduce the apparent size of Earth and make more of the sky visible at any one time, while some satellites follow Earth-trailing orbits around the Sun in order to avoid their instruments being swamped by Earth's radiation. Placing satellites in special locations called Lagrangian points ensures that Earth and the Sun remain fixed in the same orientation relative to the satellite.

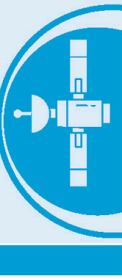
WHICH IS THE BIGGEST SPACE TELESCOPE?

Planned for launch in 2021, NASA's giant James Webb Space Telescope has a 6.4-m (21-ft) mirror. It will orbit at the Earth-Sun L1 point, four times further from Earth than the Moon.

150,000

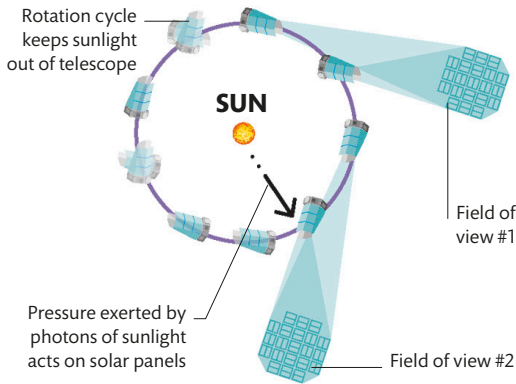
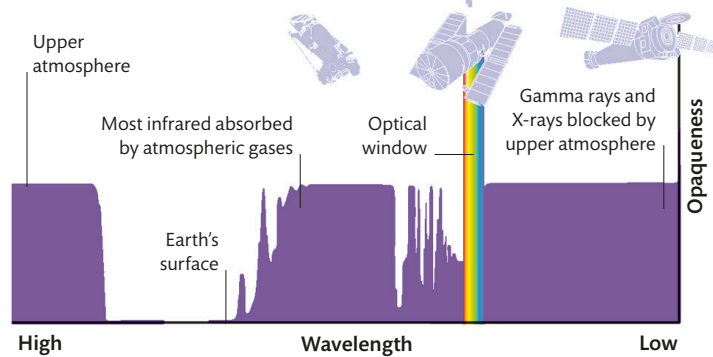
DISTANT STARS WERE
SIMULTANEOUSLY
MONITORED BY THE
KEPLER SATELLITE





DETECTING BLOCKED RADIATION

One major advantage of space-based astronomy is the ability to detect radiation that is blocked by Earth's atmosphere. High-energy electromagnetic rays beyond the near-ultraviolet are entirely absorbed by the atmosphere (fortunately for life), while at the other end of the spectrum, much infrared radiation and many longer radio waves are all absorbed. Warm water vapour in the lower atmosphere also releases infrared radiation that can swamp the weak rays from space.



Looking for planets

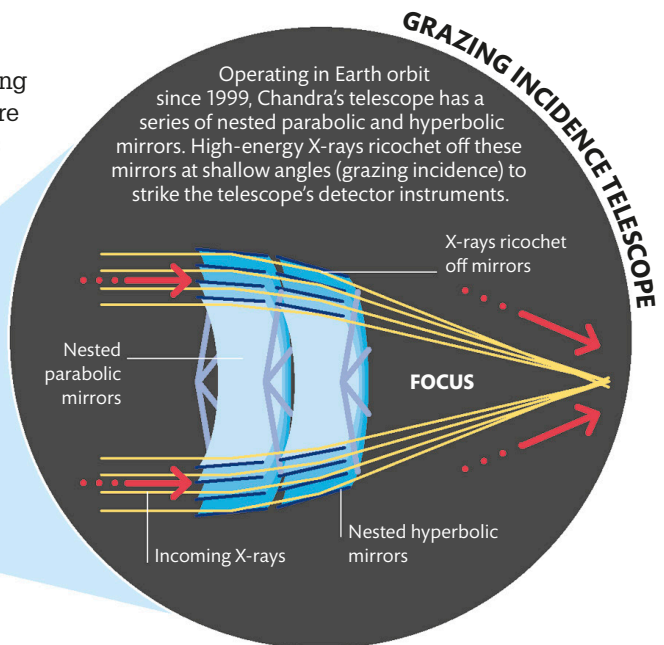
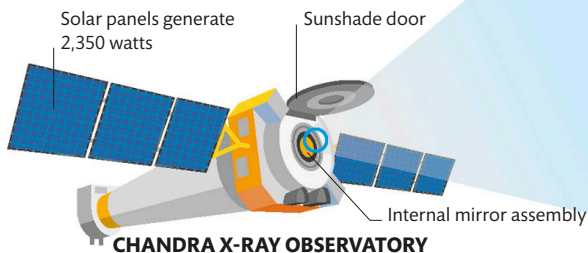
NASA's Kepler Space Telescope was a satellite launched in 2009 to detect alien planets by measuring minute dips in starlight as they pass in front of their parent stars. Placed in an Earth-trailing orbit, its initial mission involved keeping an unblinking eye on a crowded cloud of stars in the constellation Cygnus, which it did for more than three years from 2009.

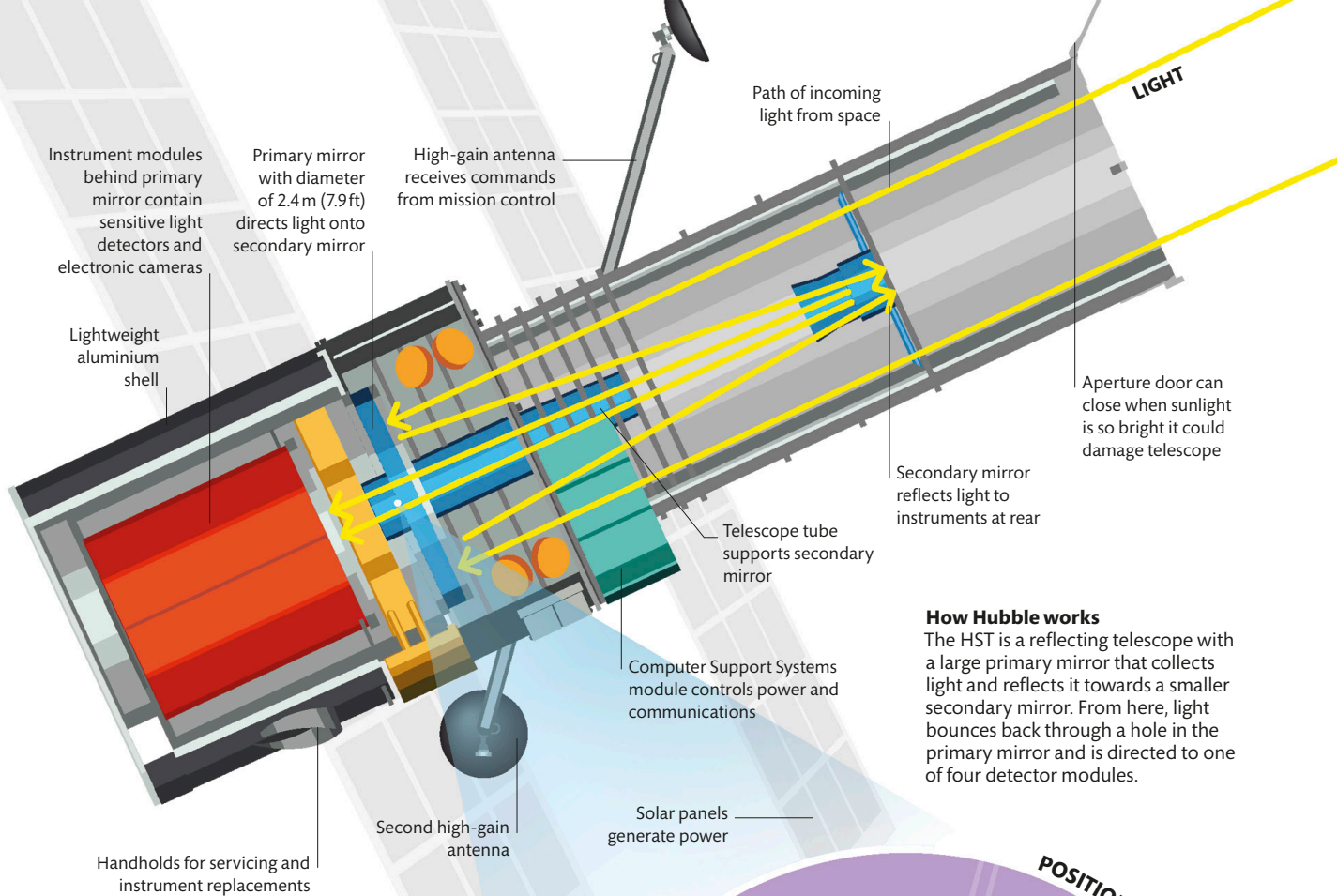
The Kepler mission

Following failures in Kepler's pointing technology in 2013, engineers found an ingenious way to stabilize it using pressure from sunlight, allowing it to continue studying different parts of the sky for shorter periods.

High-energy astronomy

High-energy astronomy satellites image the Universe using ultraviolet (UV) radiation, X-rays, and gamma rays that are produced by some of the hottest and most violent objects in space, but cannot be detected at Earth's surface. While UV can be focussed using traditional telescope designs, the energy of X-rays and gamma rays allows them to pass through normal mirrors, so other designs must be used.





How Hubble works

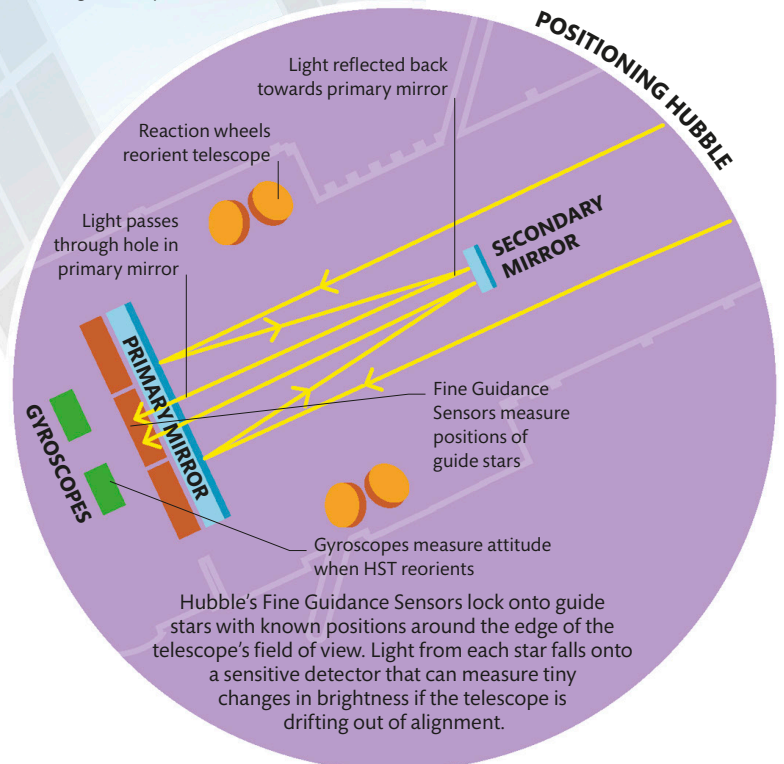
The HST is a reflecting telescope with a large primary mirror that collects light and reflects it towards a smaller secondary mirror. From here, light bounces back through a hole in the primary mirror and is directed to one of four detector modules.

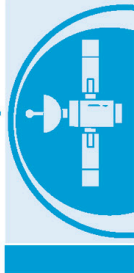
THE HST ORBITS EARTH AT AN AVERAGE SPEED OF 28,000 KPH (17,400 MPH)



Pointing the telescope

Steering and precisely pointing a telescope in space presents huge challenges. Initially, scientists working at mission control send commands to Hubble in the form of radio messages. The HST tracks its position using three Fine Guidance Sensors that measure the precise direction of known stars, alongside gyroscopes that detect the telescope's own motion or rotation. It adjusts its orientation (or corrects for drift) using weighted reaction wheels that can be spun in one direction by electric motors, causing the telescope to rotate in the other.





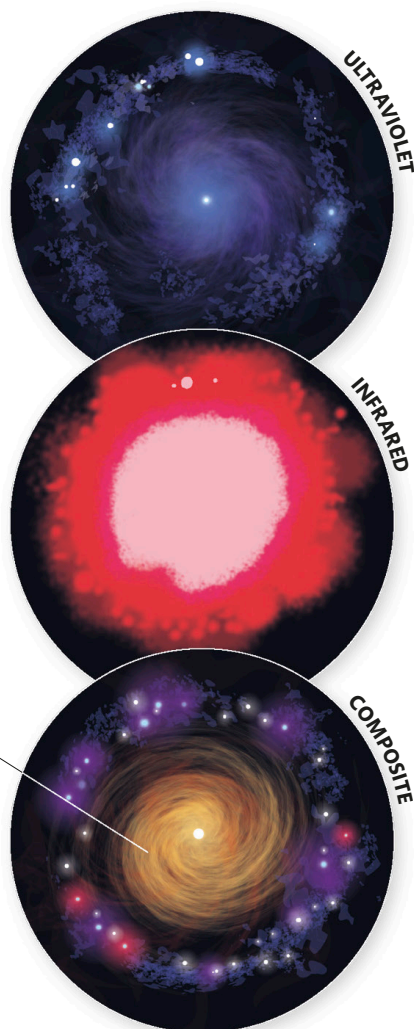
The Hubble Space Telescope

The Hubble Space Telescope (HST) is the largest and most successful space telescope (see pp.22–23), operating in Earth orbit for more than 30 years and producing thousands of discoveries that have revolutionized our understanding of the Universe.

What Hubble sees

From its location in low Earth orbit, the HST can produce images whose detail is limited only by the dimensions of its mirror and the sensitivity of its instruments. In practice, this means that, although the telescope is relatively modest by today's standards, its pictures can rival those from much larger Earth-based observatories (see pp.24–25). Furthermore, the lack of atmospheric absorption means that some of the HST's instruments can detect invisible radiation from the near-infrared to the near-ultraviolet spectrums, revealing material too cool or too hot to shine in visible light.

Composite image of spiral galaxy NGC 1512, 38 million light-years away from Earth



Wavelengths

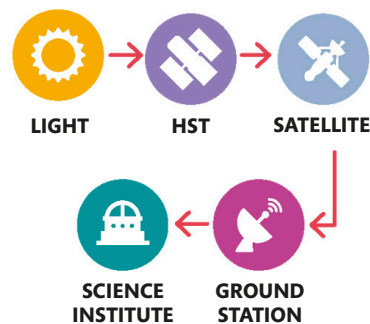
Combining near-infrared maps of relatively cool cosmic dust with ultraviolet views of a galaxy's hottest stars, the Hubble Space Telescope can build up a complete picture of structures situated in a distant galaxy.

HOW MANY TIMES HAS HUBBLE BEEN SERVICED?

Since its launch in 1990, the HST has been repaired and upgraded in space on five separate missions – most recently in 2009, shortly before the Space Shuttle was retired.

MANAGING THE DATA

Data from the various HST instruments is initially stored on the telescope itself. Every 12 hours or so, it is uploaded to one of NASA's Tracking and Data Relay Satellites in high geostationary orbit, from where it is relayed to a ground station in New Mexico, US. From here it is passed to the HST control centre in Maryland, and on to the Space Telescope Science Institute in Baltimore.

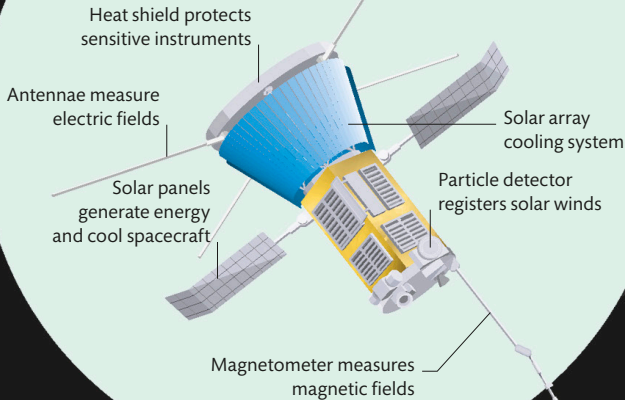


Anatomy of a space probe

A probe is a small, uncrewed spacecraft carrying scientific instruments that gather data about the environment of space and distant objects the probe visits. The instruments may detect particles, measure electrical and magnetic fields, and produce images of objects. The probe also carries subsystems that allow it to operate in space and carry out its job. These include engines for changing the probe's orientation and orbit, radio equipment to receive instructions from Earth and send back scientific data, computers to control its operations, and power systems and environmental controls to keep all systems running.

Probing the Sun

The Parker Solar Probe is a spacecraft designed to fly through the harsh environment close to the Sun, measuring magnetic fields and collecting the high-energy particles that the Sun ejects.



Space probes and orbiters

Space probes are robot spacecraft that enter another planet's atmosphere or land on the surface of another body to gather scientific data. Orbiters are not designed to penetrate the atmospheres of other bodies.

1

Gathering data

The probe is continually bombarded by fierce radiation and energetic particles - its design shields it from damaging effects while allowing it to measure conditions and detect particles.

Intense electric and magnetic fields

Hot gas outbursts from Sun

High-energy particles from solar flares

Solar wind of particles from Sun's upper atmosphere

Temperatures on heat shield reach up to 1,370°C (2,500°F)

Probe comes within 19 million km (12 million miles) of Sun

2

Communication with Earth

Data from five different scientific instruments is processed by the onboard computer and converted into electric signals. A small dish-shaped antenna sends the data to Earth via high-frequency radio waves.

Parabolic dish collects and focuses radio waves

RADIO TELESCOPE

Antenna creates electric current

3

Receiving signals

Large radio dishes on Earth receive the probe's signals. The dish focuses waves gathered across a large area onto a small receiver, which generates a weak current.

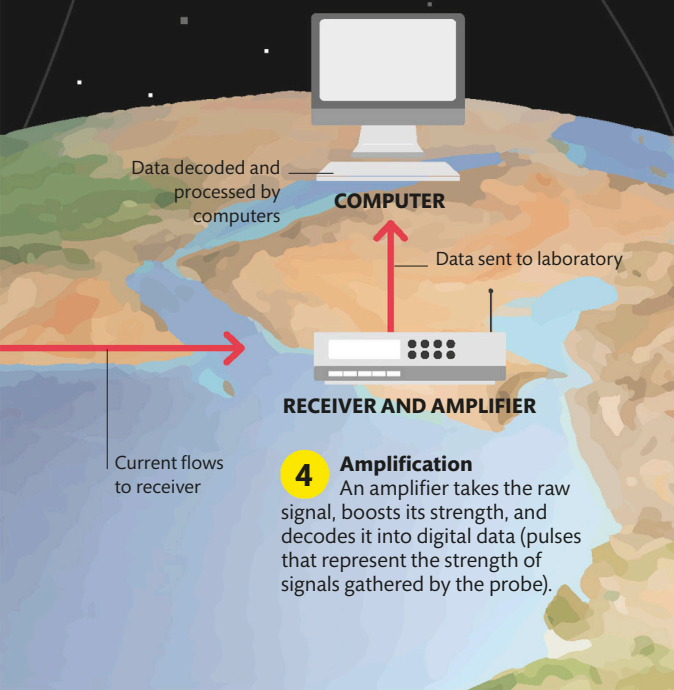
HOW LONG WOULD IT TAKE TO SEND A SPACECRAFT TO THE STARS?

Travelling at 61,000 kph (38,000 mph), the Voyager 1 spacecraft is the fastest object leaving the Solar System, but would take 70,000 years to reach the nearest star.

**THE FASTEST SPACE PROBE
EVER LAUNCHED, THE
PARKER SOLAR PROBE,
ACHIEVED A SPEED OF
393,000 KPH (244,000 MPH)**

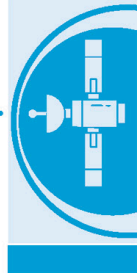
5 Decoding the data

Scientists use computers that decode the raw numbers into useful data and process it to make images, graphs, and other "data products".



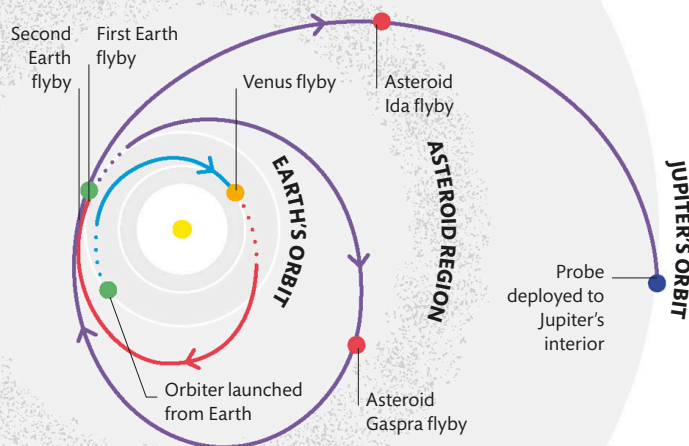
4 Amplification

An amplifier takes the raw signal, boosts its strength, and decodes it into digital data (pulses that represent the strength of signals gathered by the probe).



Reaching other worlds

In order to reach distant planets or other objects, a probe must first reach escape velocity to break free of Earth's gravity before entering a transfer orbit around the Sun (see p.181). The shape of this orbit (or a segment of it) bridges the gap to where the target object will be at a future point in time, where the spacecraft can then slow down and allow itself to be captured by its target's gravity. The different orbital speeds of objects at different distances from the Sun add to the complications.

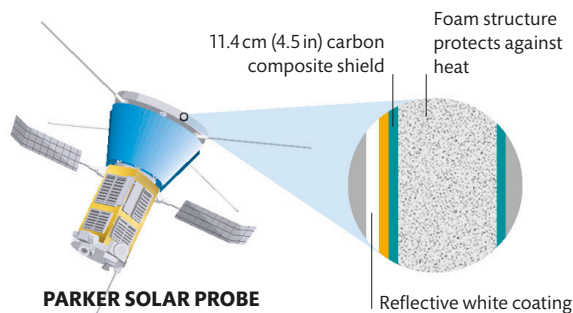


Galileo's flight trajectory

The Galileo orbiter's five-year journey to Jupiter involved two flybys of Earth and one of Venus. The orbiter altered its trajectory and gained speed on each flyby.

HEAT SHIELDING

Probes exploring the inner Solar System require thick shielding to protect instruments from the scorching heat on their sunlit sides. The design must also distribute heat to avoid stress between hot and cold parts of the spacecraft.

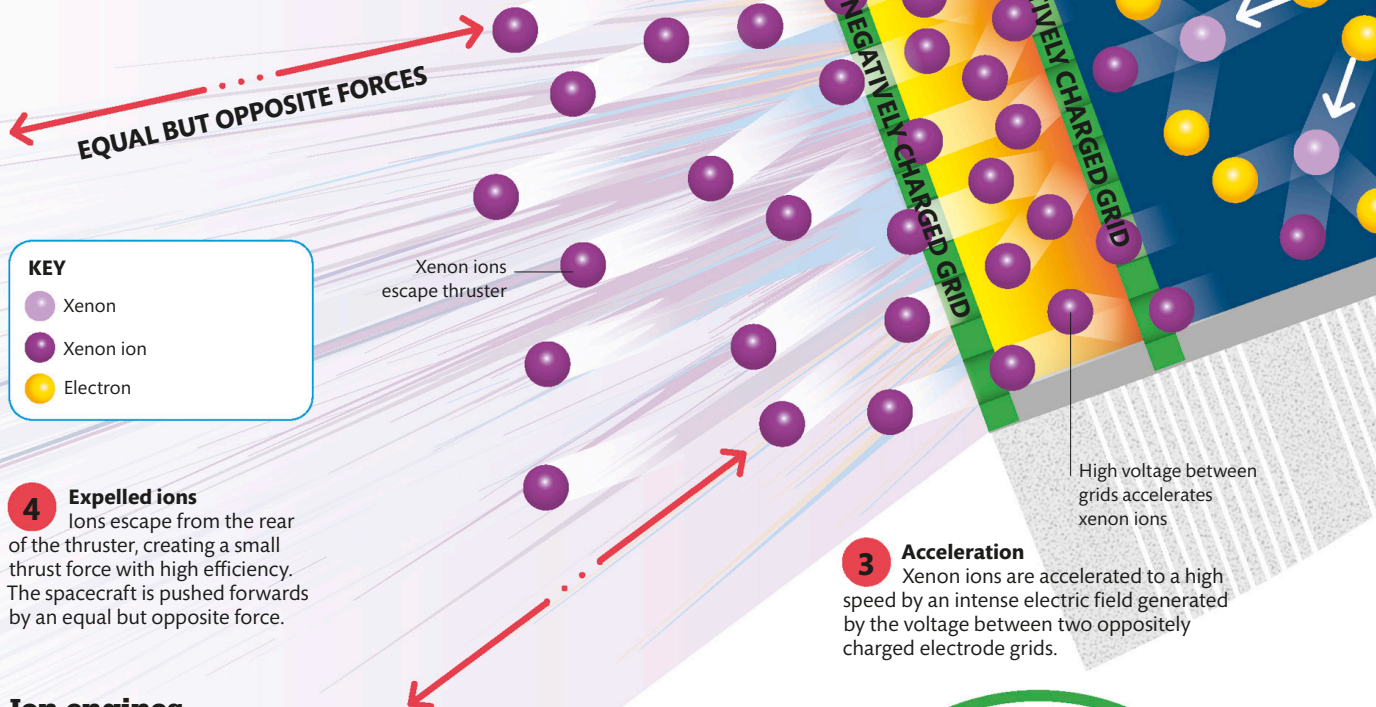


Propulsion in space

While chemical rockets are necessary to lift spacecraft away from Earth's surface, several more efficient forms of propulsion can be used in orbit and beyond.

How an ion engine works

An ion thruster transforms neutral atoms of a gas (usually xenon) into electrically charged ions. It then accelerates them to high speed in a high-voltage electric field, expelling them into space to generate thrust.



KEY

- Xenon
- Xenon ion
- Electron

4 Expelled ions

Ions escape from the rear of the thruster, creating a small thrust force with high efficiency. The spacecraft is pushed forwards by an equal but opposite force.

3 Acceleration

Xenon ions are accelerated to a high speed by an intense electric field generated by the voltage between two oppositely charged electrode grids.

Ion engines

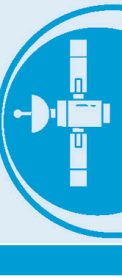
Ion thrusters generate a small amount of thrust by expelling electrically charged particles (ions) at extremely high speeds. This allows the engine to run for months with the potential to reach high speeds and cover great distances, expending only tiny amounts of fuel. Ion engines have been used in several spacecraft including the Dawn mission to the asteroids Ceres and Vesta (see pp.62–63).

THE THRUST PRODUCED BY DAWN'S ION ENGINE IS EQUIVALENT TO THE WEIGHT OF TWO SHEETS OF A4 PAPER RESTING ON YOUR HAND



HOW LONG CAN AN ION ENGINE RUN FOR?

During an 11-year mission, NASA's Dawn spacecraft ran its ion engine for a total of 5.9 years, altering its speed by a total of 41,400 km (25,700 miles) per hour.



1 Propellant released
Xenon is injected from storage tanks into an ionization chamber, where it encounters fast-moving electrons emitted by a hot, negatively charged magnetic plate known as a cathode.

Pipe from propellant tank injects xenon

Cathode heated by electricity from solar cells

Charged particles confined by magnetic field

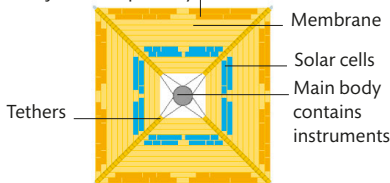
Magnet rings

2 Creating ions
Electrons collide with xenon atoms, stripping away electrons from the propellant's outer layers and transforming them into positively charged ions.

SOLAR SAILS

Solar sails harness the pressure exerted by light streaming out from the Sun. Despite lacking mass, photons of light carry momentum that can transfer to a large reflecting surface. Solar sails, like ion engines, produce tiny amounts of thrust for extremely long periods. The technology was first successfully tested in Japan's IKAROS spacecraft in 2010.

Liquid crystal device adjusts transparency



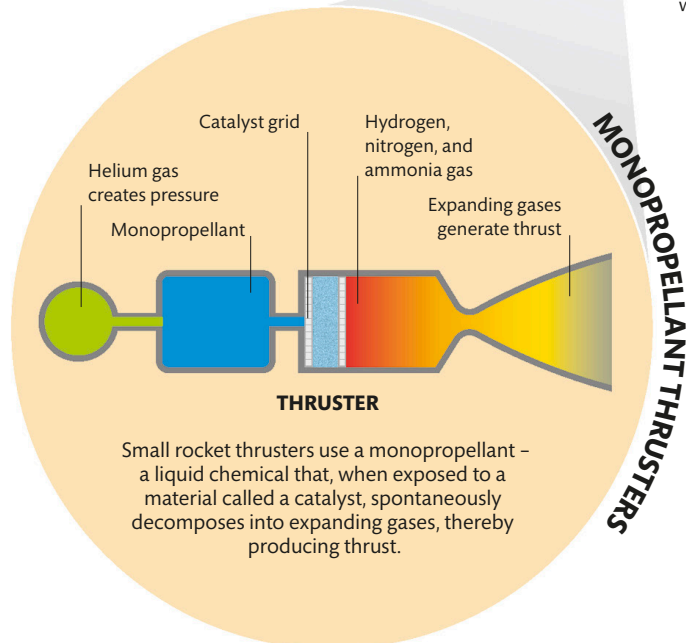
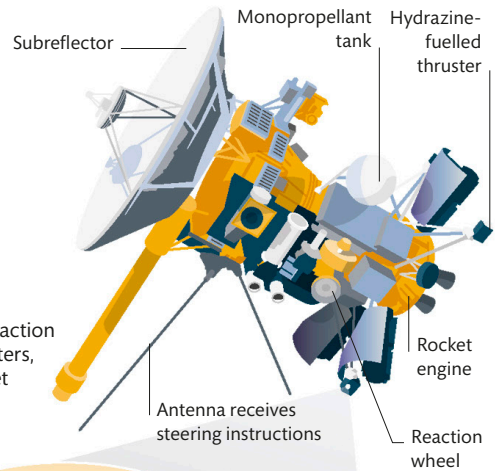
IKAROS SOLAR SAIL

Manoeuvring in space

Many spacecraft and satellites are equipped with thrusters that fire small jets of gas to push themselves around and change their orientation. Fuel is a precious commodity in space, so manoeuvres must be meticulously planned. For precise alignments, some spacecraft use reaction wheels – motorized discs that can spin around one axis, causing the spacecraft body to rotate the opposite way.

Orientation in space

A spacecraft like NASA's Cassini orbiter uses a combination of reaction wheels, hydrazine-fuelled thrusters, and a traditional chemical rocket engine to adjust its orientation.



Small rocket thrusters use a monopropellant – a liquid chemical that, when exposed to a material called a catalyst, spontaneously decomposes into expanding gases, thereby producing thrust.



Lunar Surveyor's descent

Between 1966 and 1968, NASA landed a series of Lunar Surveyor probes on the surface of the Moon, testing technologies that would later be used for the crewed Apollo missions.

Spacecraft approaches at 9,400 kph (5,840 mph)

1 Pre-retro manoeuvre

About 30–40 minutes before landing, Surveyor uses its small vernier rockets to align with its main engine facing forwards along its flight path.



2 Main retro burn

An altitude-marking radar unit triggers Surveyor's main engine to fire 75 km (47 miles) above the surface for about 40 seconds.

Doppler radar analyses lunar surface



3 Lunar contact

Vernier engines steer Surveyor to landing under control of Doppler and altimeter radars. Engines are switched off at 3.4 m (11.2 ft) and the probe drops to the lunar surface.

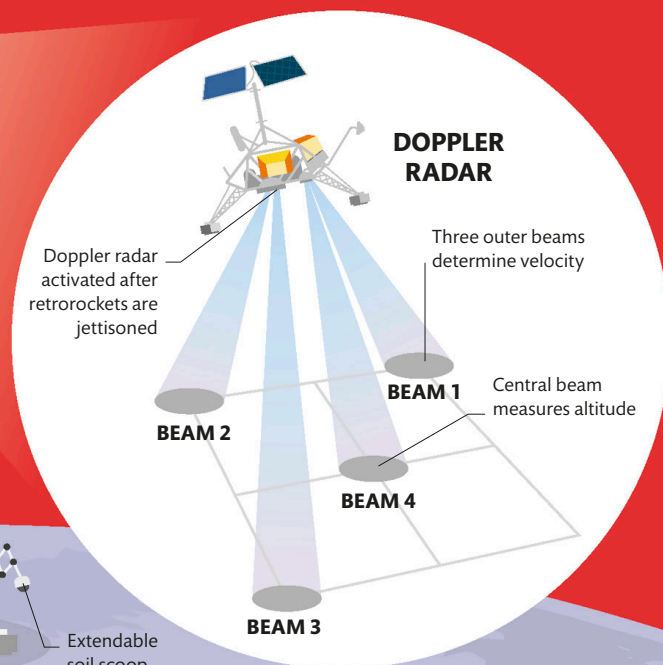
Shock-absorbing hinged legs



Extendable soil scoop

Lunar landings

In order to make a soft landing on an airless world such as the Moon, a spacecraft must first execute an engine burn against its direction of travel so that it will slow down and drop out of orbit. The approach to the surface is measured using Doppler radar, which measures not only altitude but also the spacecraft's speed of descent. Steerable vernier rockets with pivoting nozzles can then make the final approach, cutting off at a pre-set altitude or when an extended probe touches the surface.



Soft landings

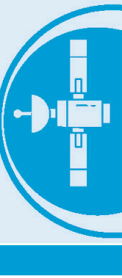
Landing on airless worlds is a relatively simple, though delicate, task. With no air resistance to reduce its speed, a spacecraft must slow its descent to the surface through the use of rockets.

ROSETTA LANDED ON COMET 67P AT A SPEED OF LESS THAN 1 M (3 FT) PER SECOND



WHAT WAS THE FIRST SOFT LANDING ON ANOTHER WORLD?

The first space probe to make a soft landing was the Soviet Union's Luna 9. It used airbags to survive a 22 kph (14 mph) impact on the Moon in 1965.

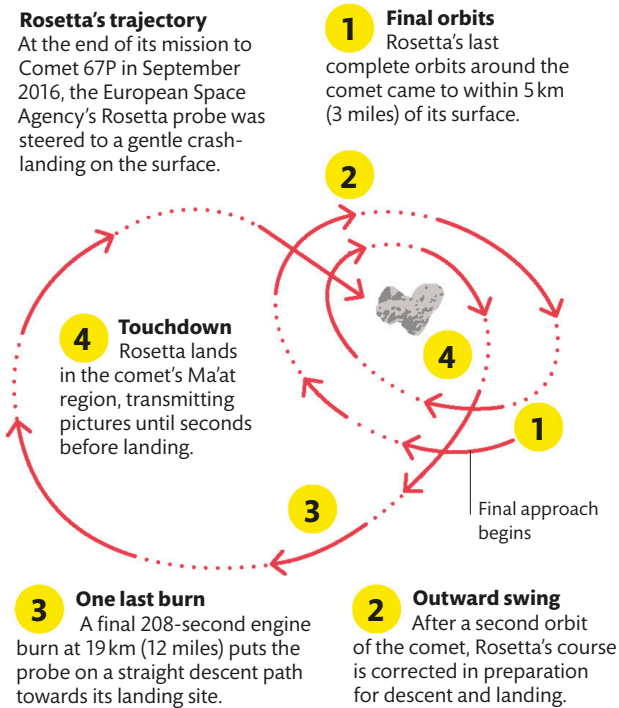


Drifting to touchdown

Spacecraft orbiting around low-gravity bodies such as comets and asteroids can simply adjust their orbits through a series of short engine burns from their thrusters. These spacecraft gradually spiral inwards in order to deliver more detailed views of the target object and eventually make a gentle touchdown on the object's surface.

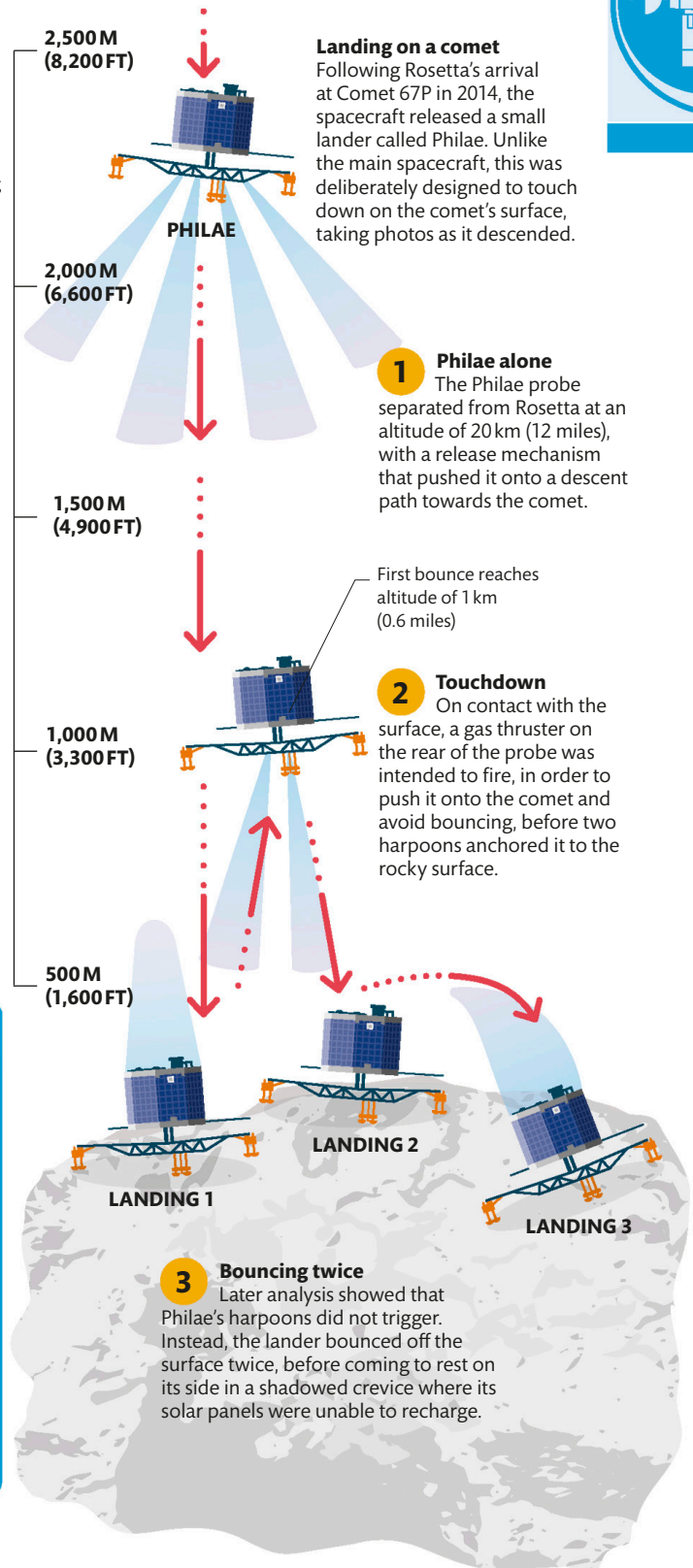
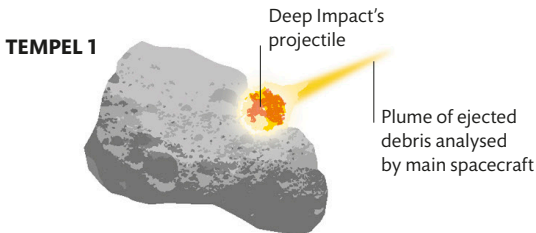
Rosetta's trajectory

At the end of its mission to Comet 67P in September 2016, the European Space Agency's Rosetta probe was steered to a gentle crash-landing on the surface.



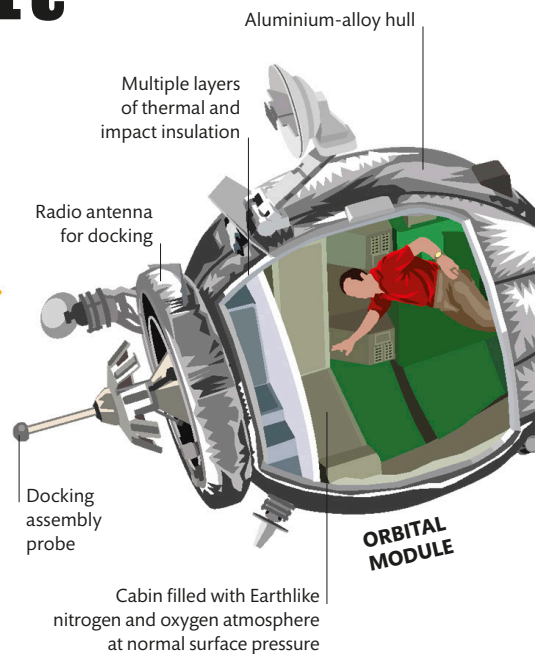
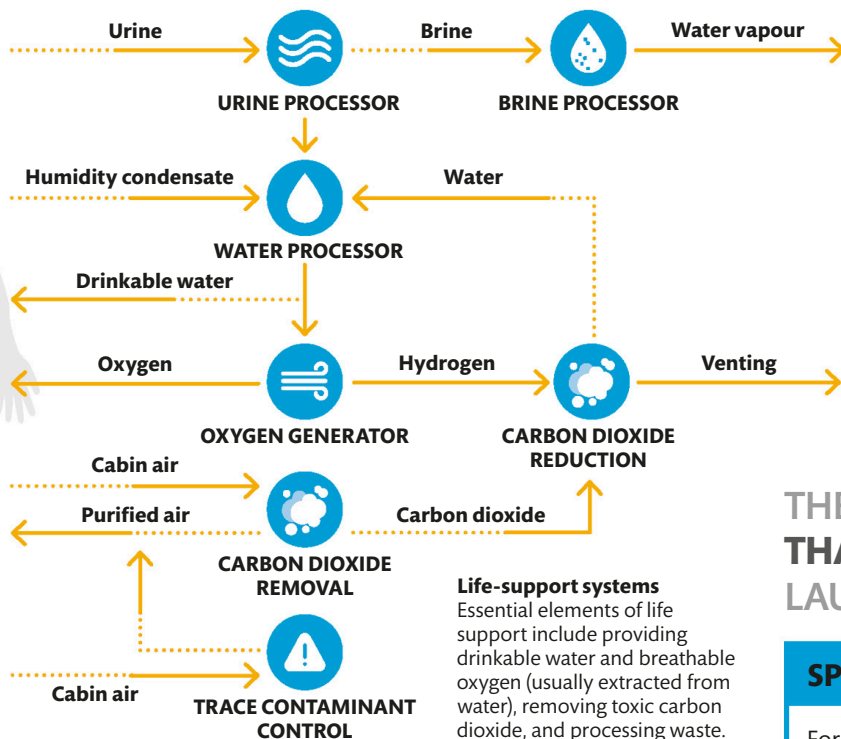
CRASH LANDINGS

Sometimes spacecraft are deliberately crashed onto a planetary surface at high speed. NASA's Deep Impact probe carried a barrel-shaped projectile that smashed into the surface of comet Tempel 1 in 2005 so the main spacecraft could study the debris thrown up.



Crewed spacecraft

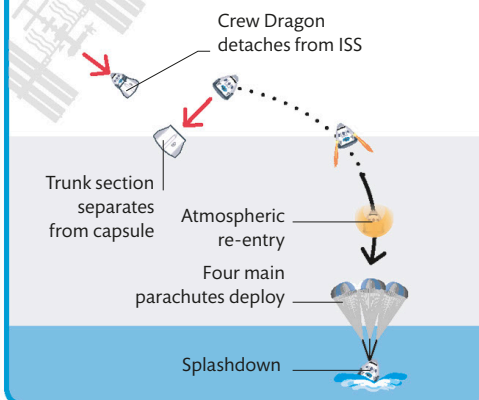
Spacecraft that carry astronauts have to be both larger and more complex than robot probes since they must carry specialized equipment to keep the astronauts alive and protect them during re-entry.



THERE HAVE BEEN MORE THAN 140 SUCCESSFUL LAUNCHES OF SOYUZ

SPLASHDOWN

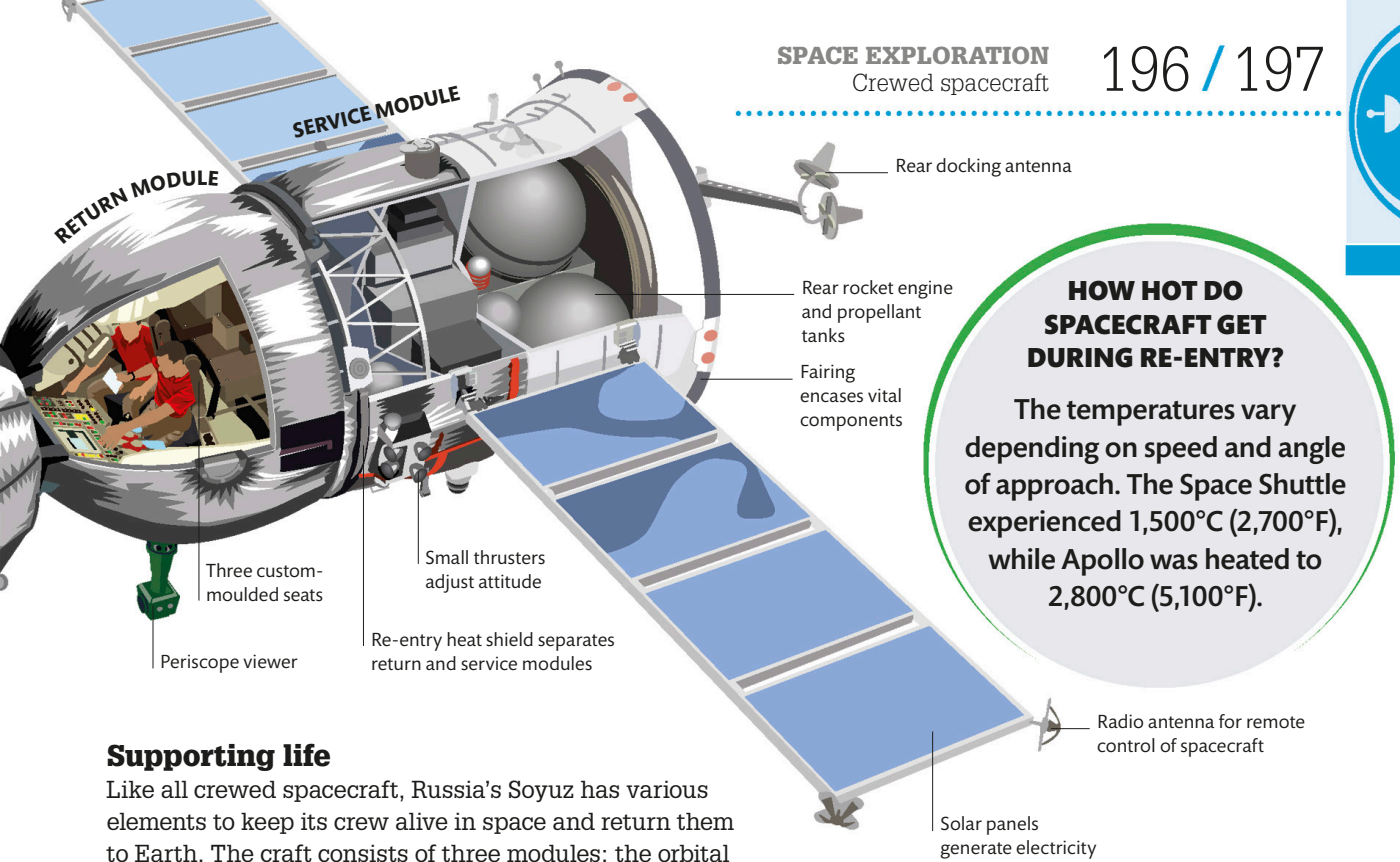
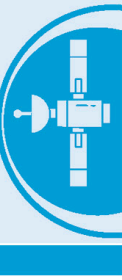
For spacecraft aiming to land in the ocean, a swift recovery is key. In 2020, SpaceX's Crew Dragon Demo-2 mission completed the first splashdown in 45 years, landing within sight of waiting recovery boats.



CREWED SPACECRAFT VEHICLES

Since the first Russian and US astronauts flew into space in 1961, there have been well over 300 successful crewed spaceflights. Although men and women of many nationalities have now become astronauts, only three countries – the United States, the Soviet Union (modern-day Russia), and China – have developed and launched their own crewed spacecraft.

	SOYUZ	APOLLO	SHENZHOU	ORION
Country	Russia	US	China	US
Crew	3	3	3	4–6
Operational	1967–present	1968–1975	2003–present	2023–
Length	7.5 m (24.5 ft)	11 m (36 ft)	9 m (30 ft)	8 m (26 ft)



HOW HOT DO SPACECRAFT GET DURING RE-ENTRY?

The temperatures vary depending on speed and angle of approach. The Space Shuttle experienced $1,500^{\circ}\text{C}$ ($2,700^{\circ}\text{F}$), while Apollo was heated to $2,800^{\circ}\text{C}$ ($5,100^{\circ}\text{F}$).

Supporting life

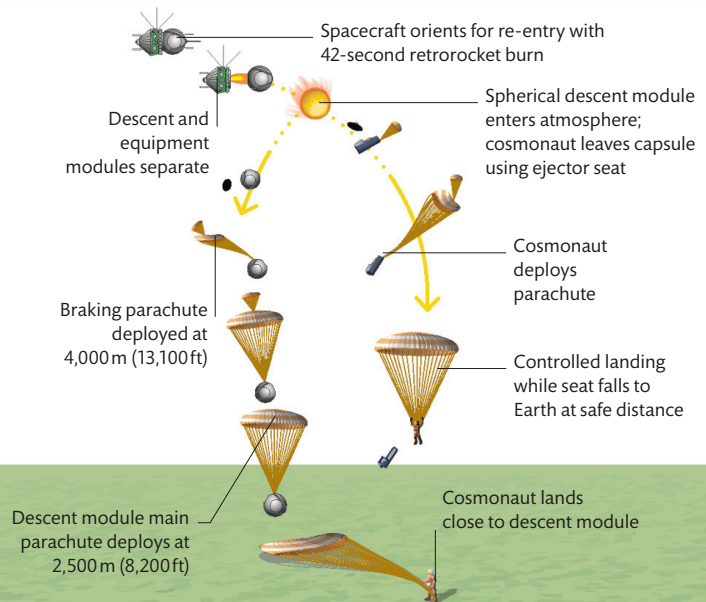
Like all crewed spacecraft, Russia's Soyuz has various elements to keep its crew alive in space and return them to Earth. The craft consists of three modules: the orbital module and aerodynamic return module are both pressurized to permit "shirtsleeve" working conditions, in which no special clothing need be worn. An unpressurized service module provides power, propulsion, and supplies for the life-support systems.

Inside Soyuz

Operated in various forms since the 1960s, Soyuz can support up to three crew members and is capable of docking with other spacecraft.

Returning to Earth

Most returning spacecraft rely on friction with the air during re-entry to slow their descent to a point where parachutes can open. The re-entry or descent module is fitted with a heat shield designed to ablate (break away, carrying heat with it), and its design is usually conical to ensure that the spacecraft aligns itself to bear the brunt of the heating on its wide base. US spacecraft have traditionally splashed down in the ocean with recovery ships standing by, while Russian and Chinese capsules returning over land use retrorockets to slow their final descent.



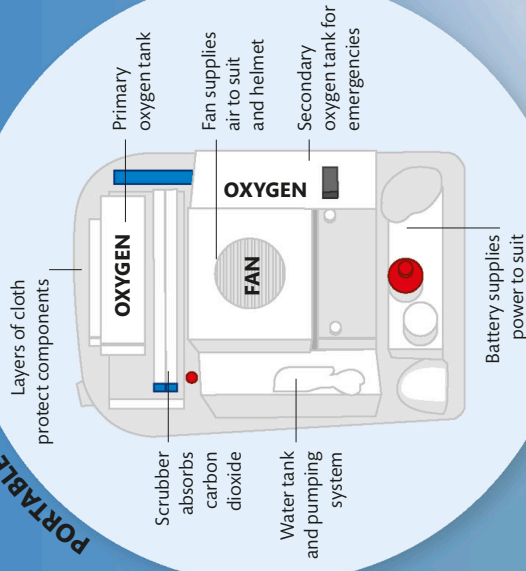
Safe landing

Cosmonauts on early Soviet spaceflights, such as Vostok 1, ejected from their spacecraft after re-entry and parachuted separately to Earth for a safe return. From 1964, Voskhod missions saw cosmonauts land in the re-entry capsule.

Spacesuit components

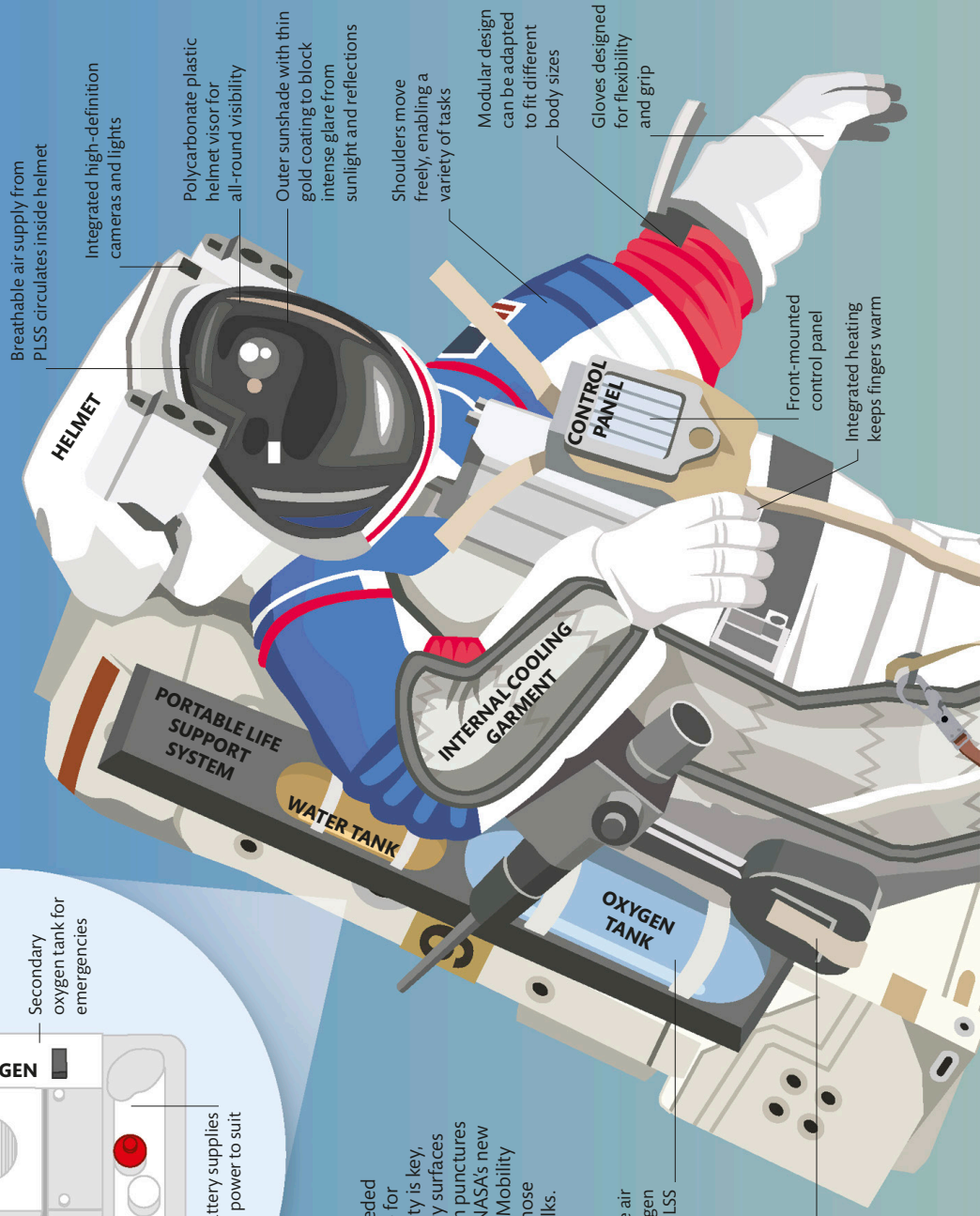
A spacesuit consists of three key elements: the pressure garment, the helmet, and a portable life support system (PLSS). The pressure garment protects the body from outside dangers, exerts pressure on the skin (in place of atmospheric pressure), and regulates temperature. The helmet provides visibility and communications and delivers air and water to the astronaut, while the PLSS provides power and consumables.

PORTABLE LIFE SUPPORT SYSTEM (PLSS)



Dressed for space

Different spacesuits are needed in different environments – for operations in space flexibility is key, while for those on planetary surfaces weight and protection from punctures are major considerations. NASA's new Exploration Extravehicular Mobility Unit (xEMU) improves on those currently used for spacewalks.



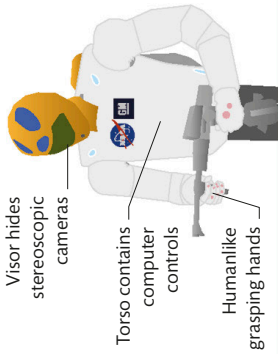
Breathable air supplied by oxygen tanks in PLSS

PLSS conceals rear-entry hatch that enables astronaut to don suit with ease



ROBONAUT

To cut the number of extra-vehicular activities (EVAs) astronauts have to perform, NASA has developed its humanoid Robonaut to carry out routine tasks in and around the International Space Station.



WHO MADE THE FIRST SPACEWALK?

Russian cosmonaut Alexei Leonov became the first person to walk in space, leaving his Voskhod 2 spacecraft for 12 minutes and 9 seconds on 18 March 1965.

The dangers of radiation

Operating beyond Earth's atmosphere and outside a spacecraft, a spacesuit must offer some degree of protection from a variety of types of harmful radiation and particles.



Cosmic rays

Fast-moving particles and high-energy radiation from outside the Solar System pass through materials.



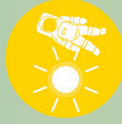
Solar flares

High-energy particles from the Sun create electromagnetic problems that disrupt electronics.



Trapped radiation

Particles in the Van Allen Belts around Earth can damage cells in an astronaut's body.



Ultraviolet radiation

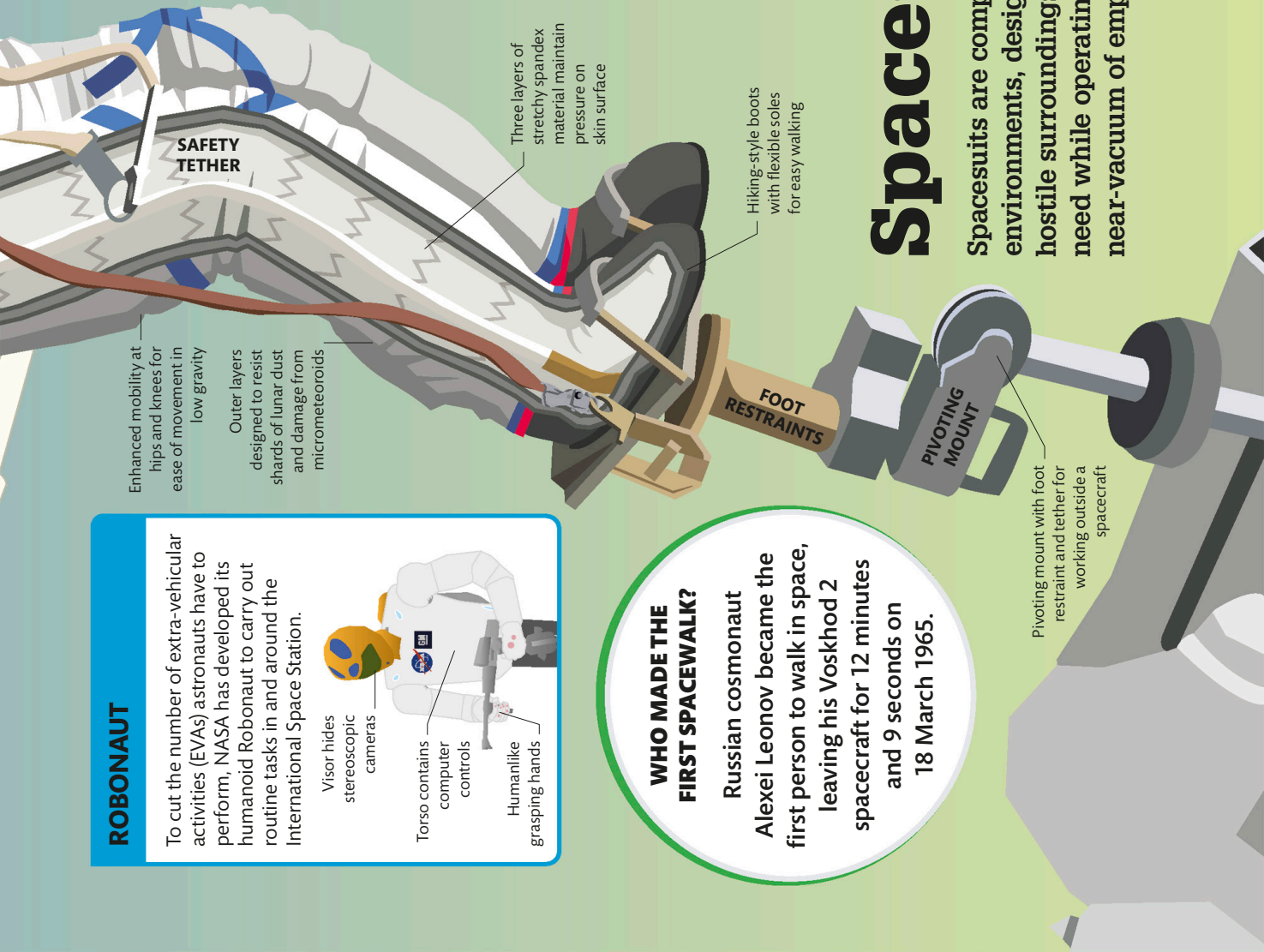
Intense visible light and strong ultraviolet radiation can damage an astronaut's eyesight.

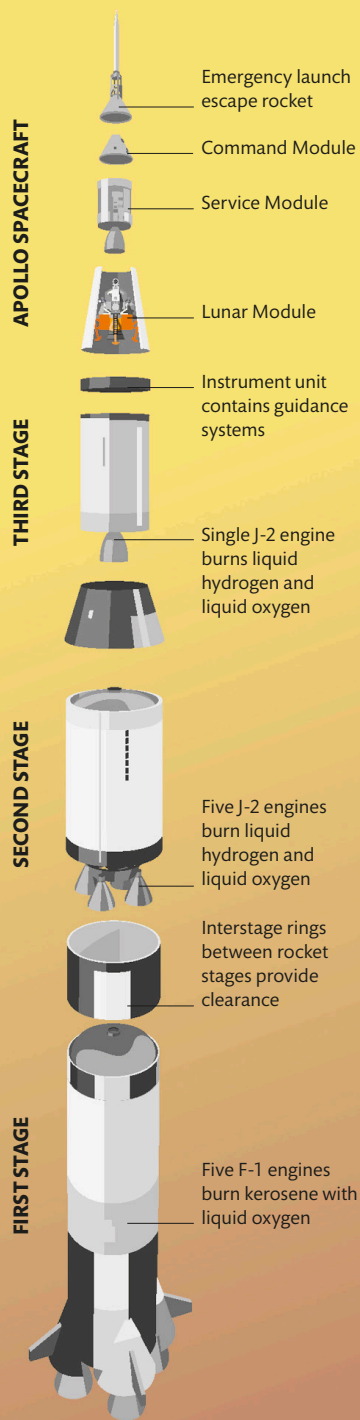


AN ASTRONAUT CAN
GROW UP TO 3% TALLER
WHILE LIVING IN SPACE

Spacesuits

Spacesuits are complete, self-contained environments, designed to protect astronauts from hostile surroundings and provide the supplies they need while operating outside their spacecraft in the near-vacuum of empty space or on another world.





Launching Apollo

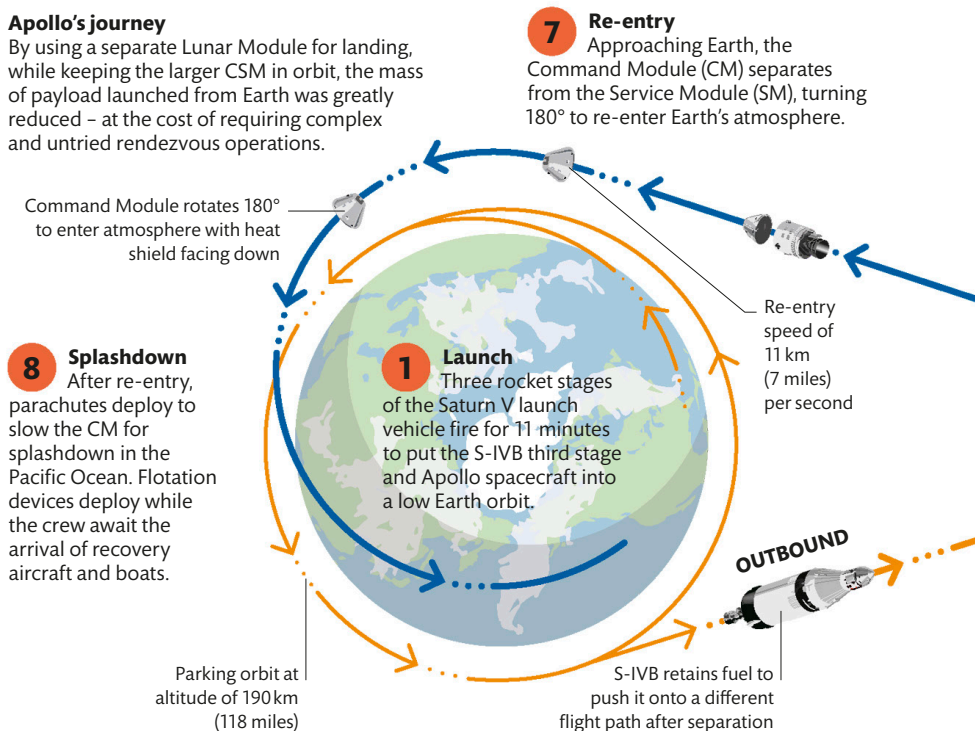
Sending Apollo to the Moon required a rocket with unprecedented power. Saturn V's three stages lifted it to Earth orbit, and once it broke free of Earth's gravity the third stage reignited to put the spacecraft on a translunar flightpath.

Mission to the Moon

Between 1969 and 1972, six US Apollo missions successfully carried astronauts to the Moon. Each expedition involved the launch of a complex three-part spacecraft using the enormous Saturn V rocket.

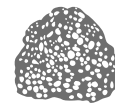
Apollo's journey

By using a separate Lunar Module for landing, while keeping the larger CSM in orbit, the mass of payload launched from Earth was greatly reduced – at the cost of requiring complex and untried rendezvous operations.

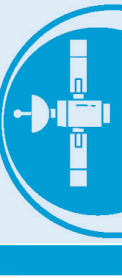


To the Moon and back

Each Apollo mission involved sending three astronauts roughly 400,000 km (250,000 miles) to the Moon. One crew member remained in lunar orbit aboard the Command and Service Module (CSM), while the other two descended to the surface in the Lunar Module (LM). At the end of surface operations, the upper half of the LM blasted off to rendezvous with the CSM in lunar orbit for the return to Earth. Finally, the Command Module separated from the rest of the spacecraft for atmospheric re-entry.



THE SIX APOLLO MISSIONS BROUGHT A TOTAL OF 382 KG (842 LB) OF MOON ROCK BACK TO EARTH

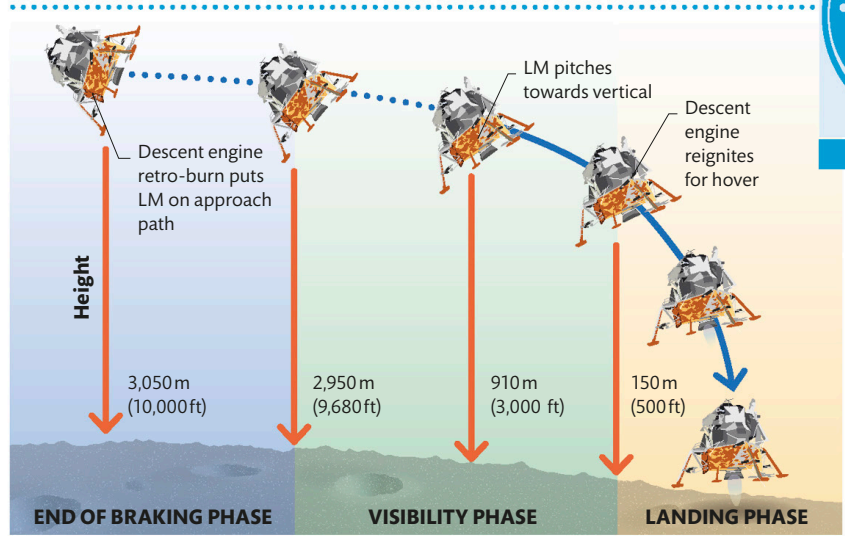


Lunar lander

Designed to fly only in a near-vacuum, the ungainly Apollo Lunar Module consisted of a spiderlike Descent Stage and a pressurized Ascent Stage designed to carry two astronauts. Each stage had its own engine, allowing the Ascent Stage to return to lunar orbit at the end of its surface mission.

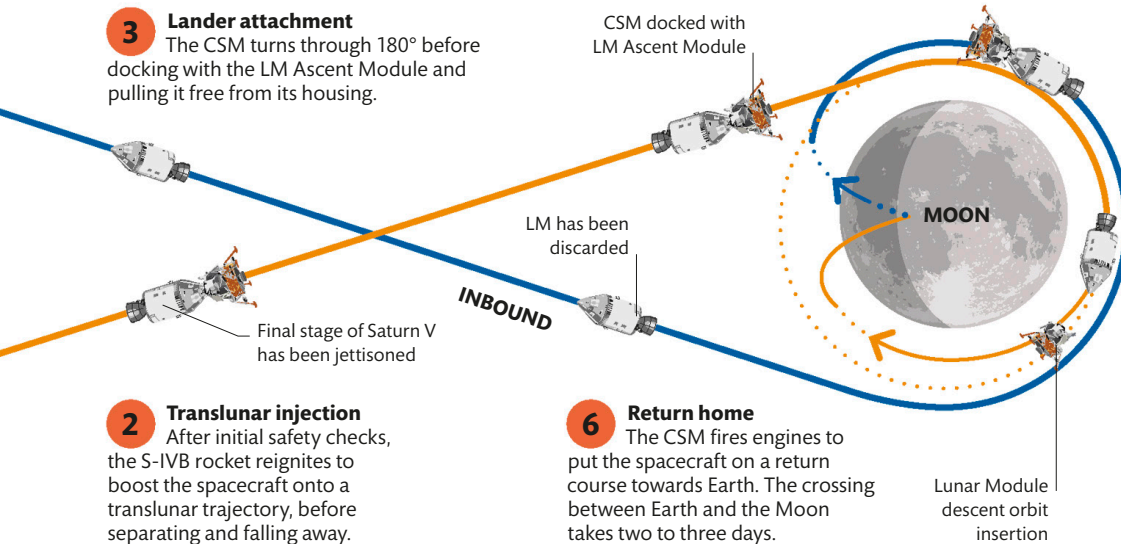
Landing on the lunar surface

The final stages of descent to the lunar surface involved precise piloting using the main descent engine and four reaction control thrusters – small multidirectional rockets positioned around the Ascent Stage.



3 Lander attachment

The CSM turns through 180° before docking with the LM Ascent Module and pulling it free from its housing.



2 Translunar injection

After initial safety checks, the S-IVB rocket reignites to boost the spacecraft onto a translunar trajectory, before separating and falling away.

6 Return home

The CSM fires engines to put the spacecraft on a return course towards Earth. The crossing between Earth and the Moon takes two to three days.

4 Orbit and landing

A CSM engine burn slows the spacecraft to put it into lunar orbit. Two astronauts board the LM and descend to the surface.

5 Lunar orbit rendezvous

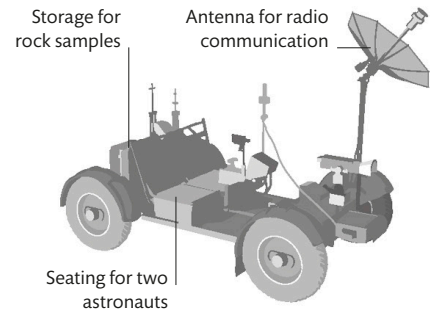
The LM Ascent Stage blasts off after the surface mission and docks with the CSM in lunar orbit. Astronauts and samples are transferred before the LM is discarded.

HOW MANY TESTS WERE PERFORMED BEFORE THE LANDING?

Only four crewed Apollo missions, numbered 7-10, flew before the Moon landing to test the spacecraft in Earth and lunar orbit.

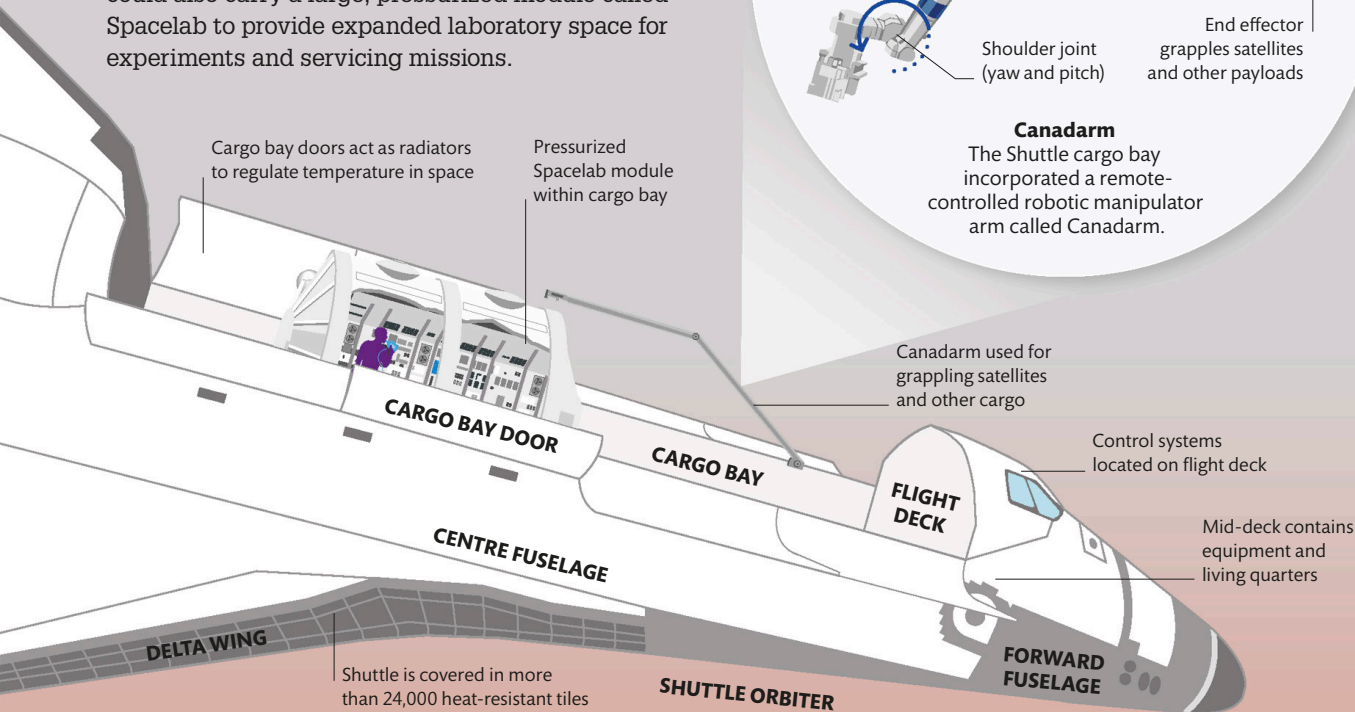
THE LUNAR ROVING VEHICLE

The final three Apollo missions carried a Lunar Roving Vehicle that extended the range of exploration around the landing site. The lightweight but robust battery-powered vehicle could carry about twice its own weight and achieve a top speed of 18 kph (11 mph).

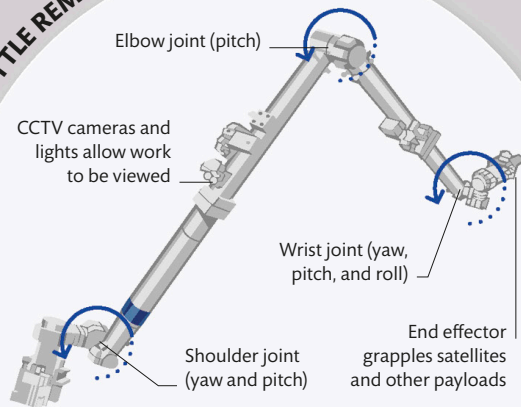


The Shuttle at work

Once in space with its typical crew of around seven astronauts and payload specialists, the Shuttle orbiter was capable of carrying out a wide variety of different tasks. A large, pressurized cabin area provided living quarters as well as room to house some experiments, while the huge, depressurized cargo bay could be used to carry experiments, deploy satellites and retrieve them from orbit for servicing, and deliver components for the International Space Station. The cargo bay could also carry a large, pressurized module called Spacelab to provide expanded laboratory space for experiments and servicing missions.



SHUTTLE REMOTE MANIPULATION SYSTEM

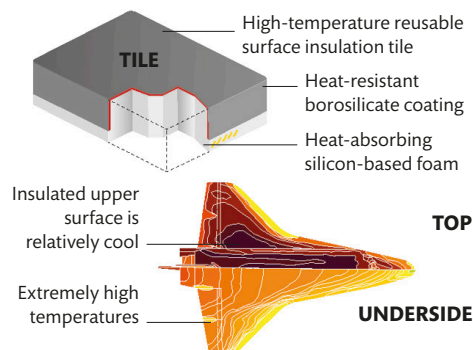


Canadarm

The Shuttle cargo bay incorporated a remote-controlled robotic manipulator arm called Canadarm.

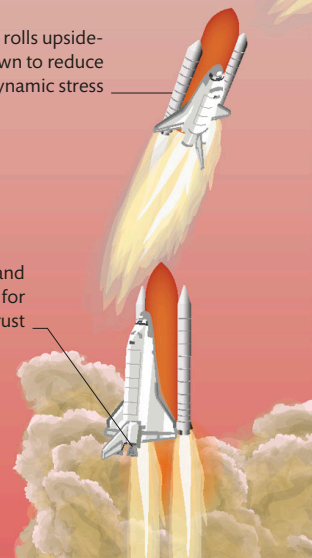
THERMAL PROTECTION SYSTEM

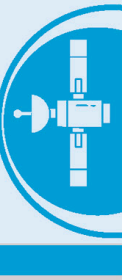
While other spacecraft use heat shields that break away and carry heat with them during re-entry, the orbiter's hull was protected by several types of permanent insulation. The ceramic tiles used for the hottest areas proved vulnerable to damage and wear, and resulted in one disastrous failure.



Shuttle rolls upside-down to reduce aerodynamic stress

Main engines and SRBs ignite for launch thrust





The Space Shuttle

NASA's Space Shuttle was a revolutionary launch system that combined conventional rockets with a reusable spaceplane the size of a small airliner. The Shuttle provided the US with access to space from 1981 to 2011.

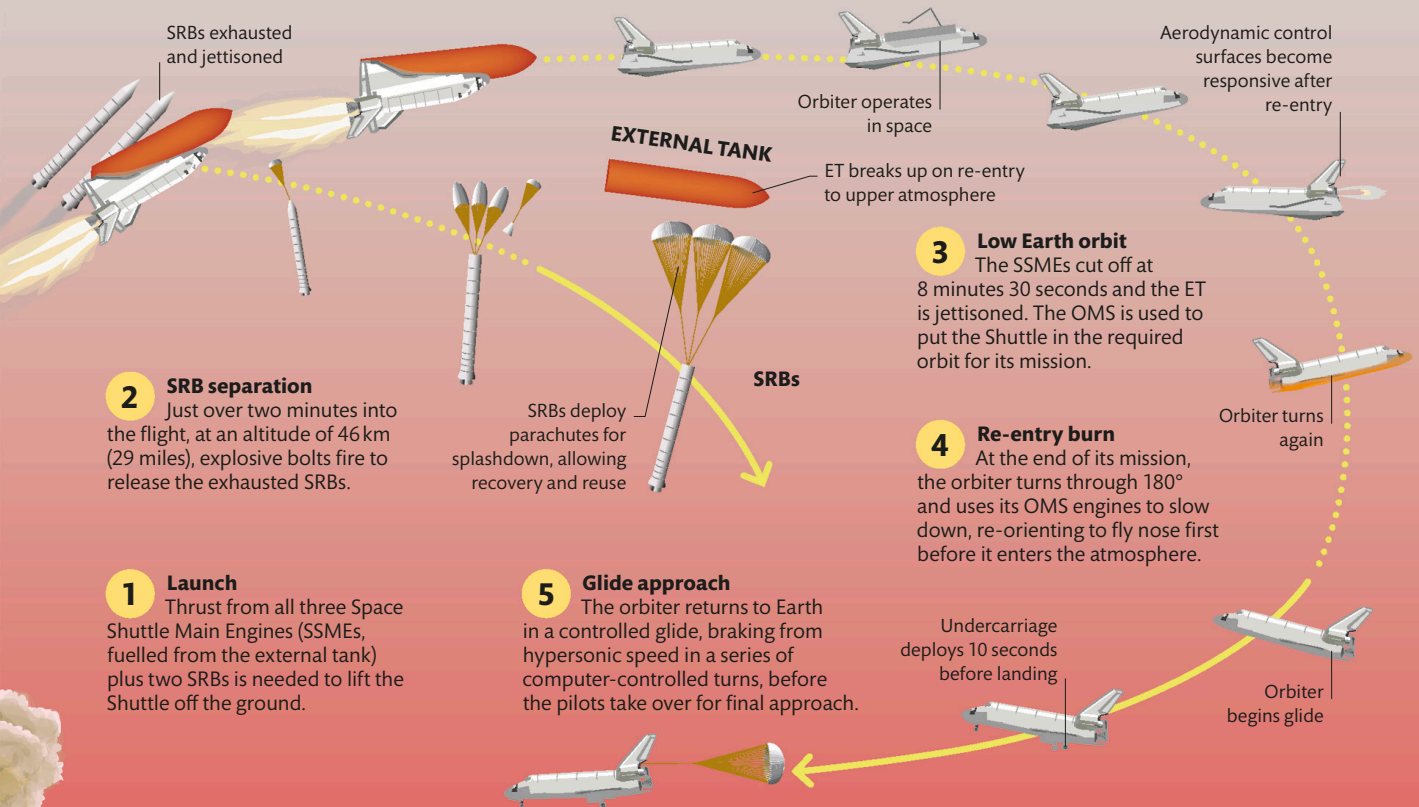
Mission profile

The Space Shuttle launched vertically, with the orbiter strapped to a large external fuel tank (ET) that delivered fuel to the orbiter's three main engines. Solid rocket boosters (SRBs) attached to either side of the ET aided the launch. Once in space, the Shuttle used its Orbital Manoeuvring System (OMS) to complete operations. After a week or more in space, the orbiter reversed its orientation and fired its main engines to re-enter Earth's atmosphere, returning to a horizontal landing as an unpowered glider.

HOW MANY SPACE SHUTTLES WERE THERE?

NASA's fleet included four flight-worthy orbiters – initially, *Columbia*, *Challenger*, *Discovery*, and *Atlantis* (plus the prototype *Enterprise*). Two Shuttles were lost in accidents, and in 1992 *Endeavour* was built.

WEIGHING 110 TONNES (121 TONS) AT LAUNCH, THE SHUTTLE ORBITER WAS BY FAR THE HEAVIEST SPACECRAFT EVER PUT INTO ORBIT

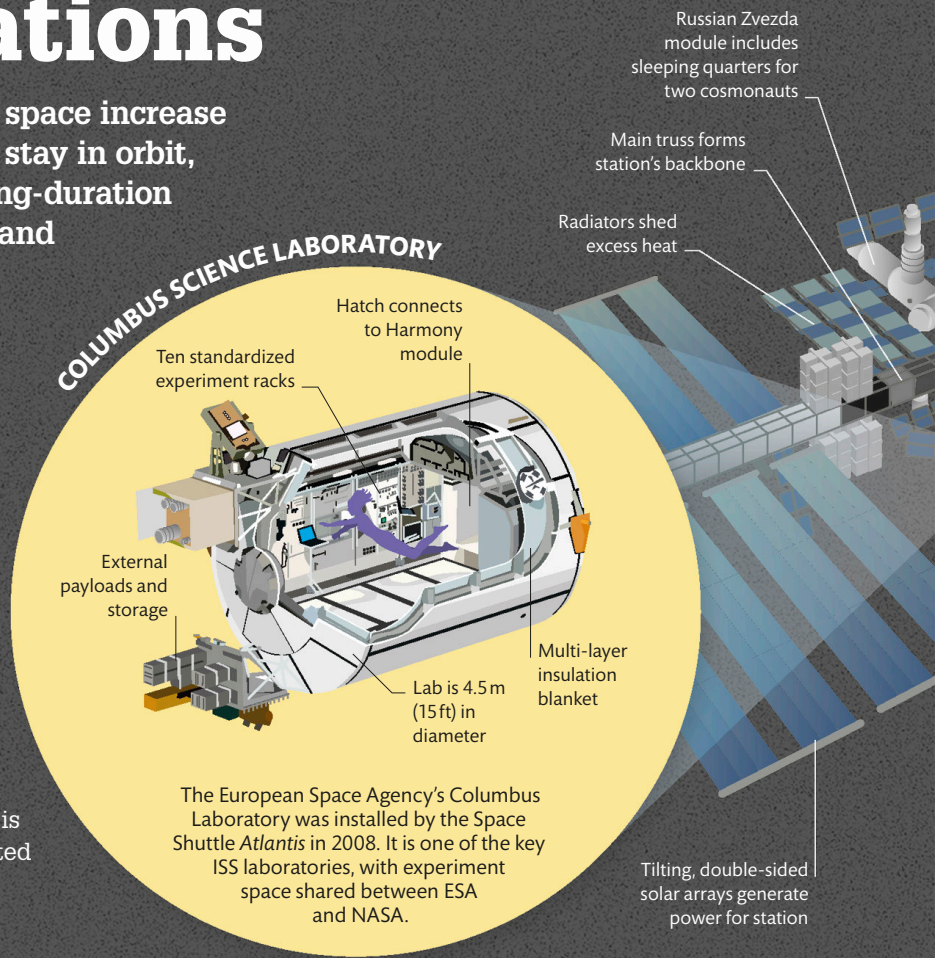


Space stations

Semi-permanent outposts in space increase the time that astronauts can stay in orbit, allowing them to conduct long-duration experiments in zero-gravity and the near-vacuum of space.

The International Space Station

The biggest space station ever built, the International Space Station (ISS) circles Earth in low Earth orbit. Fifteen pressurized modules, including European, US, Russian, and Japanese laboratories, provide living and working space for an average crew of six astronauts. They are connected to the main beam, called a truss structure. On its exterior, the station has multiple robotic arms for various tasks, alongside areas for exposing experiments to space. Power is supplied by tilting solar panels connected to the truss, with a span wider than a football pitch.



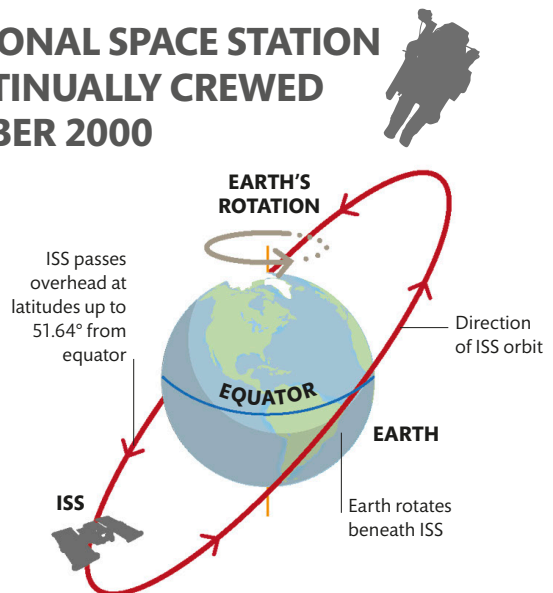
Getting into orbit

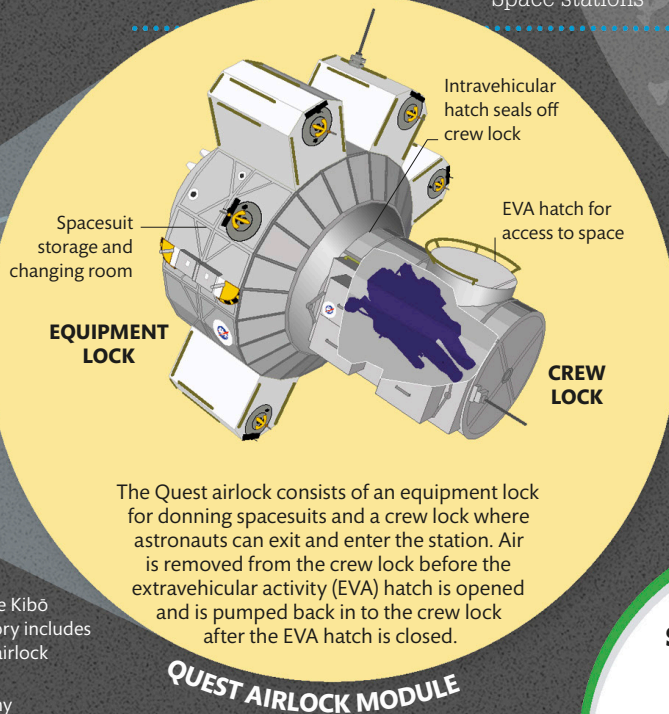
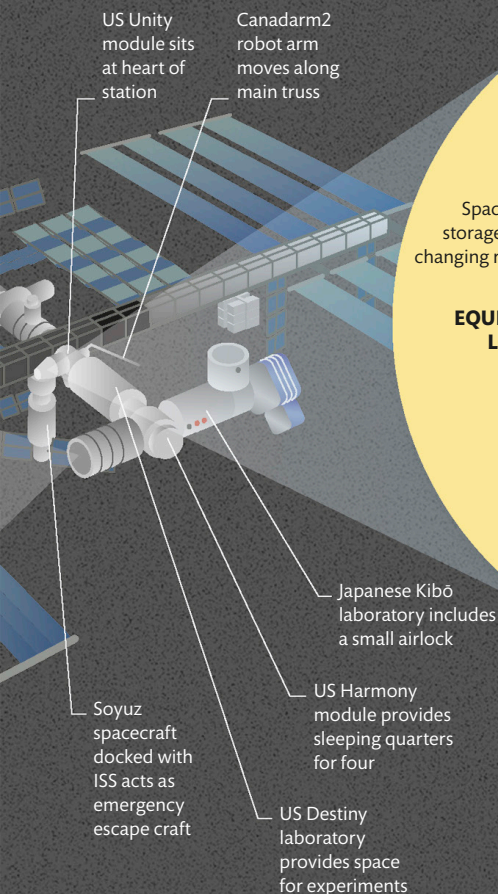
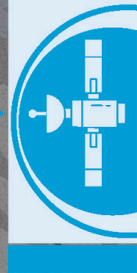
Building the ISS was the most complex engineering task ever undertaken in space. Main construction lasted from 1998 to 2011, with the US Space Shuttle playing a crucial role in delivering components and linking them together with its robotic arm. Crews (usually groups of three overlapping each other in six-month expeditions) initially arrived on the Shuttle or Russian Soyuz spacecraft. In 2011 Soyuz became the sole means of access, but commercial space vehicles are now taking some of the burden.

THE INTERNATIONAL SPACE STATION HAS BEEN CONTINUALLY CREWED SINCE 31 OCTOBER 2000

Orbiting the Earth

The ISS orbits at an average altitude of 409 km (254 miles) above Earth, tilted at an angle of 51.6° relative to Earth's equator. This means it circles the Earth once every 92.7 minutes, or 15.5 times every day. The station has an average orbiting speed of 27,724 kph (17,227 mph).





QUEST AIRLOCK MODULE

Inside the ISS

The ISS is a self-contained village in space, built as a collaboration between NASA and the Russian Space Agency with contributions from other space agencies around the world. The main phase of the station's construction involved 31 separate rocket launches and Space Shuttle assembly flights.





WHO HAS SPENT THE LONGEST CONTINUAL TIME IN SPACE?

Cosmonaut Valery Polyakov spent 438 consecutive days in space from 1994–95 aboard the Russian Mir space station.

Earth-orbiting space stations

The Salyut space stations of the 1970s followed a basic Soviet military design with a single airlock. In 1973, NASA launched a competitor with Skylab, based on leftover Apollo hardware. Salyut 6 (1977) was the first station with two airlocks, allowing crews to visit or swap over without the station being left empty. Mir (1988–2001) was a forerunner to the ISS design, with multiple pressurized units in a modular arrangement.

OTHER EARTH-ORBITING SPACE STATIONS

Name	Country	Launch date	Information
 Salyut 1	USSR	April 1971	The first in a series of space stations based on a design called Almaz, Salyut 1 was abandoned after its first crew died during their return to Earth.
 Skylab	USA	May 1973	NASA's Skylab was adapted from a spare Saturn rocket stage and damaged during launch. It was repaired by its first crew and visited by two more in 1973–74.
 Mir	USSR	February 1986	Built over the course of a decade, Mir grew to incorporate seven pressurized modules. In the 1990s, US Space Shuttles docked with the station.
 Tiangong-1	China	September 2011	The prototype Chinese space station Tiangong-1 was visited by one automated spacecraft and two crewed Shenzhou missions during two years of operation.

Landing on other worlds

Successfully landing on the surface of another world often requires far more complex systems than just retrorockets – especially so when the atmosphere is substantially thicker or thinner than Earth's.

Curiosity on Mars

The challenges of reaching the Martian surface vary with the size of spacecraft involved. Mars's atmosphere creates substantial friction, so an incoming probe must be shielded from the heat. It is too thin for parachutes alone to slow down the heaviest landers, but sufficiently dense to create instability if relying on retrorockets. The Curiosity rover combined a variety of techniques to ensure a safe touchdown.

1

Mars final approach

The Curiosity rover, safely encased in a two-part aeroshell, separates from the cruise stage in orbit and descends towards the Martian surface.

416 seconds to touchdown

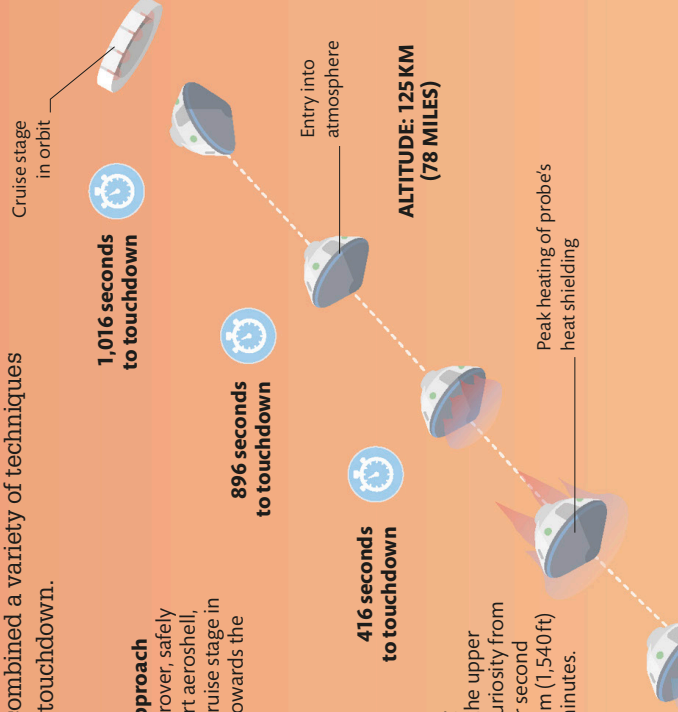
2

Aerobraking

Friction with the upper atmosphere slows Curiosity from 5.8km (3.6 miles) per second down to around 470m (1,540ft) per second in four minutes.

Landing on Mars

Curiosity's descent combined aerobraking, parachutes, and a complex device called a Sky Crane in an operation that, once triggered, took place with no direct control from Earth.

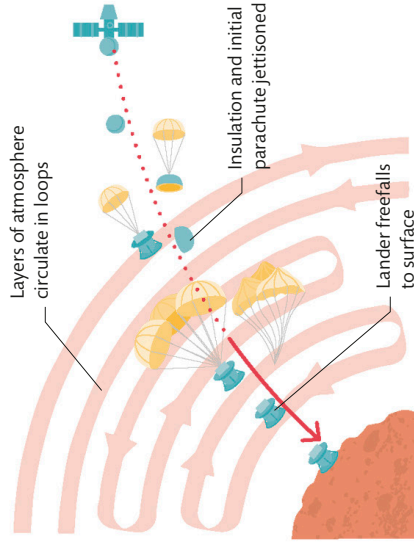


WHO MADE THE FIRST LANDING ON VENUS?

The Soviet Union's Venera 7 was the first soft-landing probe to reach the surface of Venus intact, sending back data for just 20 minutes.

Landing on Venus

Landing on Venus is even more hazardous than reaching Mars. The atmosphere is thicker and better able to support a parachute, but also highly toxic and corrosive. Nevertheless, a series of heavily shielded Venera spacecraft made safe descents in the 1970s and 1980s.

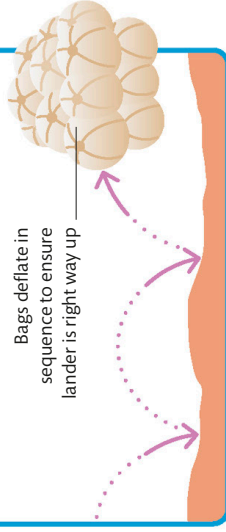


A hazardous descent

Venera landers used a combination of aerobraking and parachutes to reach the surface of Venus. The thick atmosphere cushioned the final 50-km (30-mile) fall.

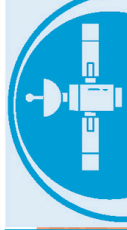
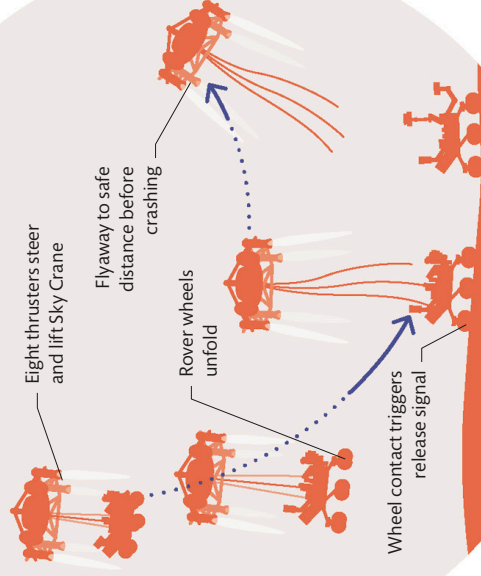
BOUNCING DOWN ON MARS

In 2004, a pair of rovers arrived on Mars by using a combination of aerobraking, parachutes, and retrorockets, finally dropping to the surface encased in airbags.



SKY CRANE DESCENT

The Sky Crane system lowered Curiosity to a gentle, soft landing on the surface of Mars before flying away.



Heat shield separates and radar begins data collection

ALTITUDE: 11 KM (7 MILES)

Parachute diameter 16 m (52 ft)

162 seconds to touchdown

ALTITUDE: 10 KM (6 MILES)

3 Parachutes

A parachute deploys at supersonic speed and unfolds, slowing the probe's descent to about 100 m (330 ft) per second.

138 seconds to touchdown

4 Sky Crane

In the final descent phase, the rover is transported to its landing site beneath a flying platform called the Sky Crane.

Powered descent

ALTITUDE: 1.8 KM (1.1 MILES)

Rover lowered beneath Sky Crane from 20 m (65 ft)

CURIOSITY ENTERED THE MARTIAN ATMOSPHERE AT A SPEED OF 5.8 KM (3.6 MILES) PER SECOND





SOJOURNER

Length: 65 cm (2 ft)



SPIRIT AND OPPORTUNITY

Length: 1.6 m (5 ft)



CURIOSITY

Length: 3 m (10 ft)



PERSEVERANCE

Length: 2 m (6.5 ft)

Rover sizes

Rovers vary in size and complexity depending on the objectives of their missions on Mars.

Electricity generated by heat from decay of radioactive plutonium stored inside power unit

Wheels can surmount obstacles up to 65 cm (26 in) high

Mars rovers

Until humans can safely explore other planets, wheeled mobile robots, called rovers, are the next best alternative. So far humans have sent five rovers to the planet Mars, each one more sophisticated, and capable of answering more complex scientific questions, than the last.

The Curiosity Mars Rover

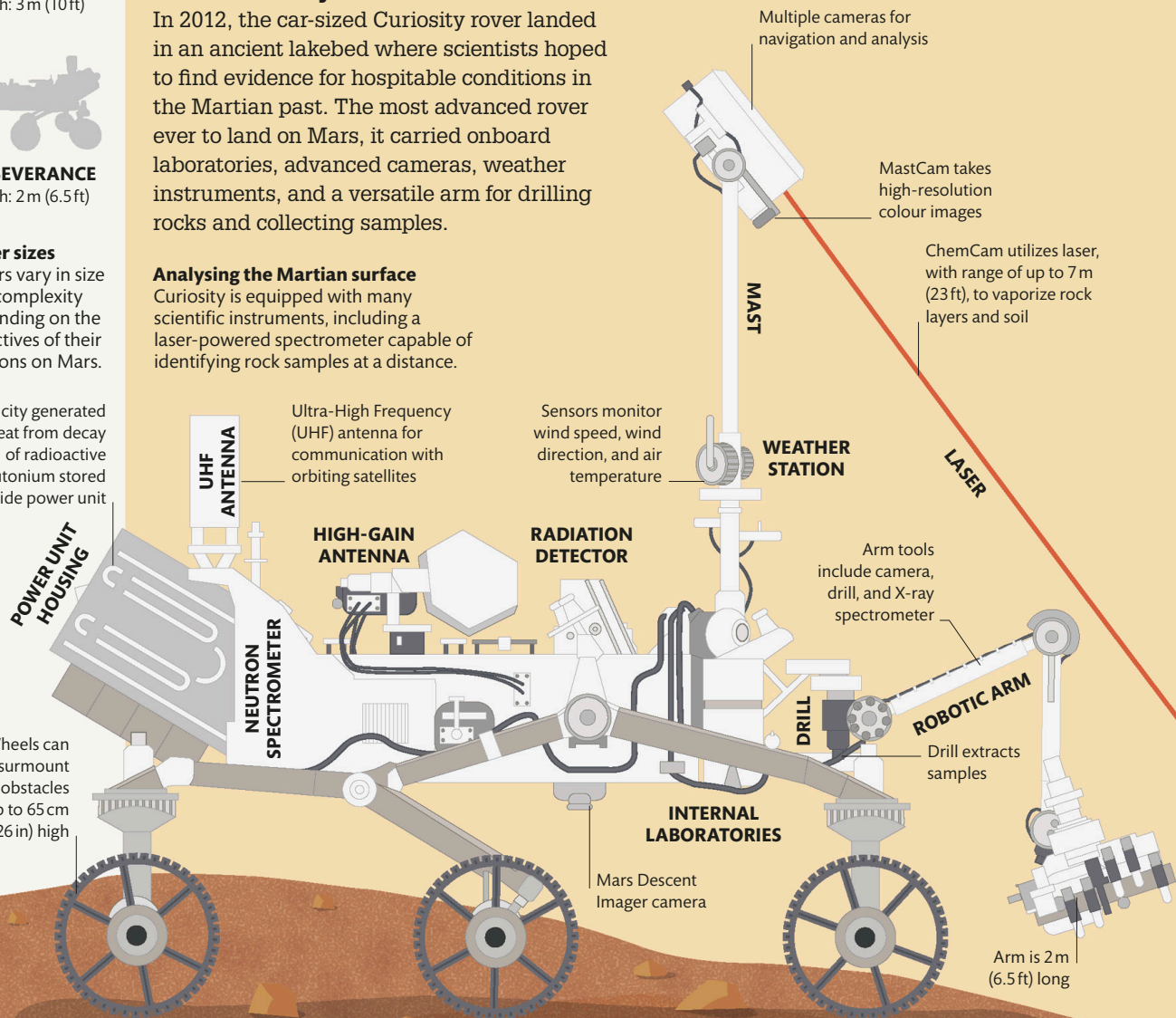
In 2012, the car-sized Curiosity rover landed in an ancient lakebed where scientists hoped to find evidence for hospitable conditions in the Martian past. The most advanced rover ever to land on Mars, it carried onboard laboratories, advanced cameras, weather instruments, and a versatile arm for drilling rocks and collecting samples.

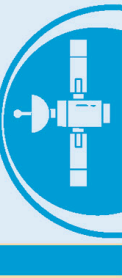
Analysing the Martian surface

Curiosity is equipped with many scientific instruments, including a laser-powered spectrometer capable of identifying rock samples at a distance.

WHAT WAS THE FIRST ROVER ON ANOTHER WORLD?

The USSR's Lunokhod 1 was a solar-powered vehicle that landed on the Moon in November 1970. It operated for almost ten months.

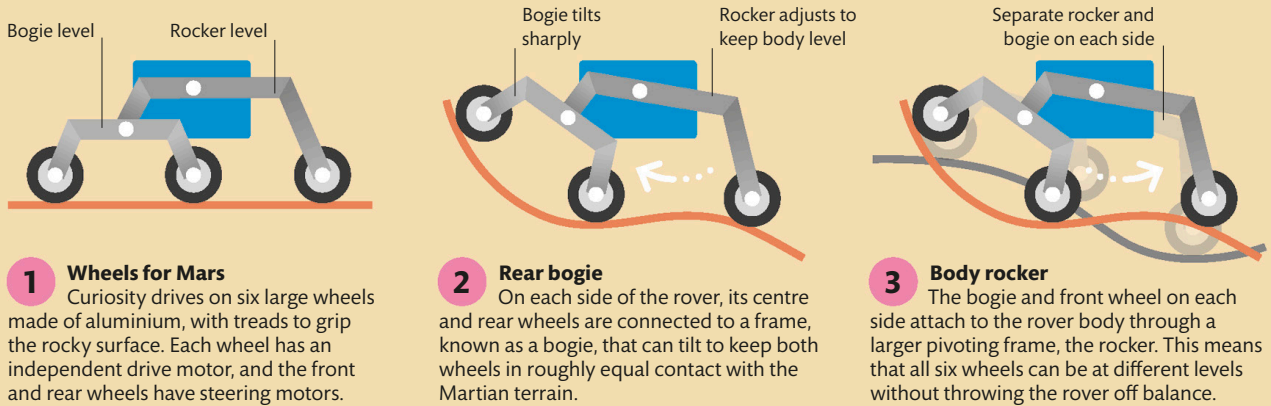




Driving on Mars

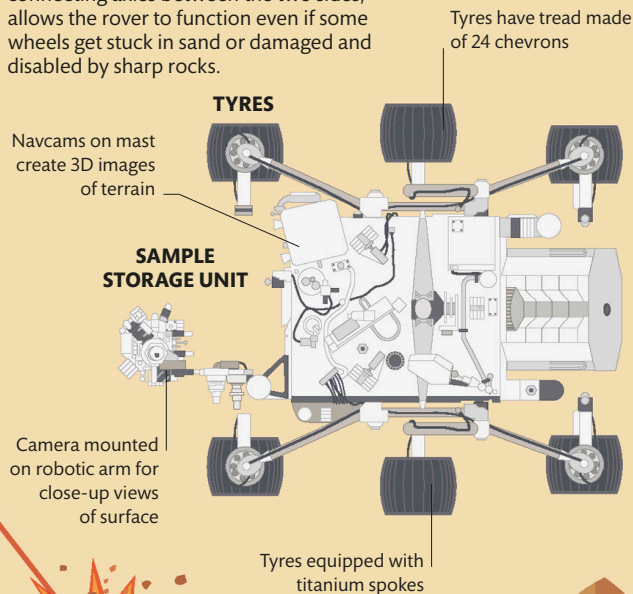
In order to navigate the uneven surface of Mars, rovers are equipped with a rocker-bogie suspension system to keep level. The delay in sending radio signals back and forth to Earth means that engineers cannot steer the vehicle in real time – instead they gather data and images before planning a course to each new waypoint. The rover then follows this route, using sensors and its onboard computer to navigate minor hazards along the way.

**CURIOSITY HAS A
TOP SPEED OF JUST
90 M (295 FT)
PER HOUR**



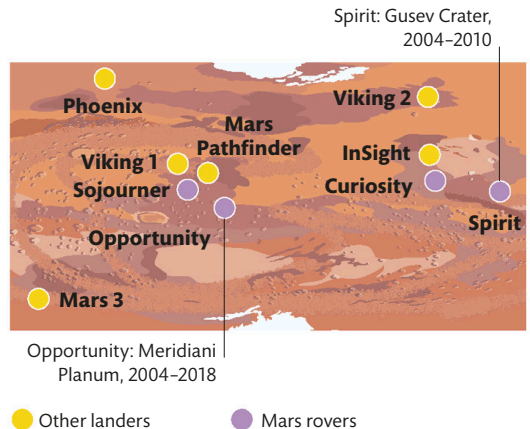
Overhead view

Curiosity's six-wheel drive, with no connecting axles between the two sides, allows the rover to function even if some wheels get stuck in sand or damaged and disabled by sharp rocks.



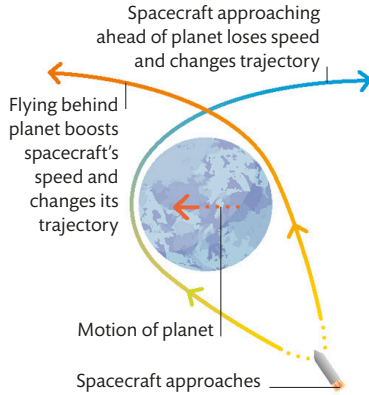
OTHER ROVERS ON MARS

The first rover to land on Mars, in 1997, was the small solar-powered Sojourner, part of the Mars Pathfinder mission. This was followed by the larger Mars Exploration Rovers Spirit and Opportunity, in 2004, Curiosity (the Mars Science Laboratory) in 2012, and Perseverance, launched in 2020.



GRAVITATIONAL SLINGSHOTS

The Voyagers relied on a technique called the gravity assist or slingshot. This allows a spacecraft to alter its direction and speed without an engine burn by falling into the gravitational field of a moving planet at just the right angle. From the point of view of the planet, the spacecraft approaches and leaves at the same speed, but relative to the Sun and wider Solar System, its speed is altered.



WHY DID VOYAGER 1 NOT GO TO URANUS AND NEPTUNE?

NASA scientists wanted at least one Voyager spacecraft to investigate Saturn's giant moon Titan. This required an approach trajectory that aimed below Saturn's south pole, which deflected the spacecraft out of the plane of the Solar System.

Planetary alignment

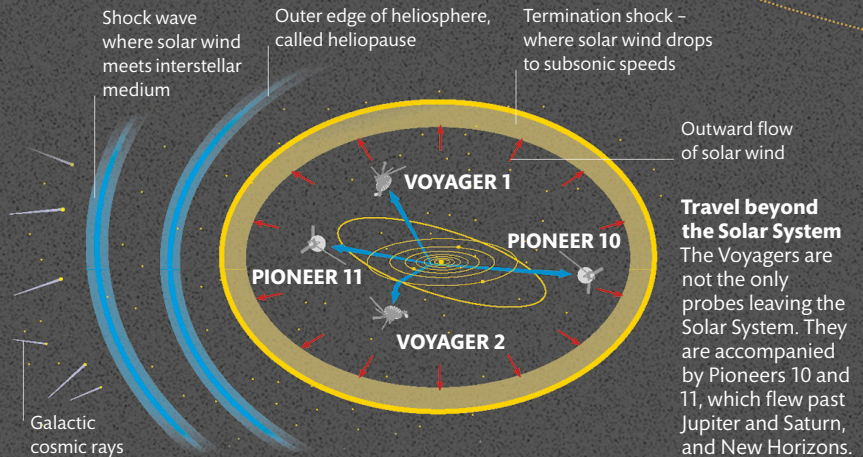
The Voyager missions were made possible by a grand alignment of all four outer planets in the late 1970s that saw Jupiter, Saturn, Uranus, and Neptune arranged along a spiral trajectory. This alignment, which only happens every 175 years, made it possible for each spacecraft to fly past each planet in turn without using huge amounts of fuel to alter their flight path.

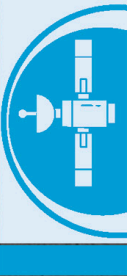
Grand tours

Launched in 1977, the two Voyager spacecraft provided humanity with a first detailed look at the giant planets of the outer Solar System. They continue to send back valuable scientific data even today.

Interstellar missions

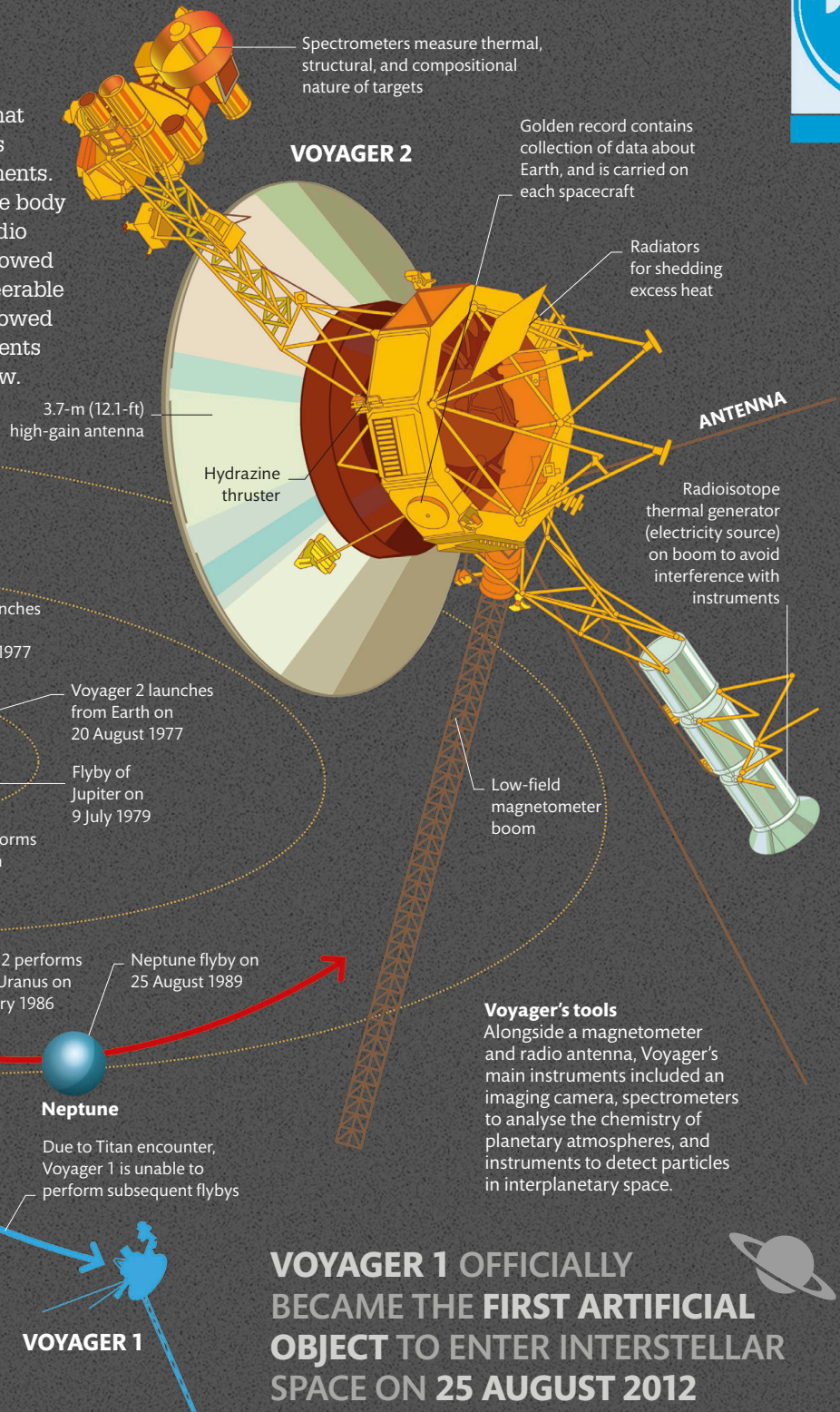
Although the Voyager spacecraft are now well beyond the orbits of the planets, they are still sending back valuable information about conditions at the edge of the Solar System. This is where the heliosphere – the region filled by the solar wind of particles flowing out from the Sun at high speeds – merges into interstellar space. Both probes will continue to transmit data until their electricity supplies run out in the mid-2020s.





The Voyager spacecraft

Each Voyager probe was built around a decahedral (10-sided) that held the main spacecraft systems and most of the scientific instruments. Long antennae emerging from the body measured magnetic fields and radio waves, while an antenna dish allowed communication with Earth. A steerable platform on the end of a boom allowed cameras and some other instruments to keep planets and moons in view.



Voyager 1 performs Saturn flyby and encounters Titan on 12 November 1980

Flyby of Jupiter on 5 March 1979

Voyager 1 launches from Earth on 5 September 1977

Voyager 2 launches from Earth on 20 August 1977

Flyby of Jupiter on 9 July 1979

Voyager 2 performs Saturn flyby on 26 August 1981

Voyager 2 performs flyby of Uranus on 24 January 1986

Neptune flyby on 25 August 1989

Voyager's tools

Alongside a magnetometer and radio antenna, Voyager's main instruments included an imaging camera, spectrometers to analyse the chemistry of planetary atmospheres, and instruments to detect particles in interplanetary space.

Planetary pinball

After launching from Earth, the two Voyager spacecraft flew past first Jupiter and then Saturn. Voyager 2 continued to Uranus and Neptune, while Voyager 1 was deflected onto a path that took it out of the plane of the Solar System.

VOYAGER 1 OFFICIALLY BECAME THE FIRST ARTIFICIAL OBJECT TO ENTER INTERSTELLAR SPACE ON 25 AUGUST 2012

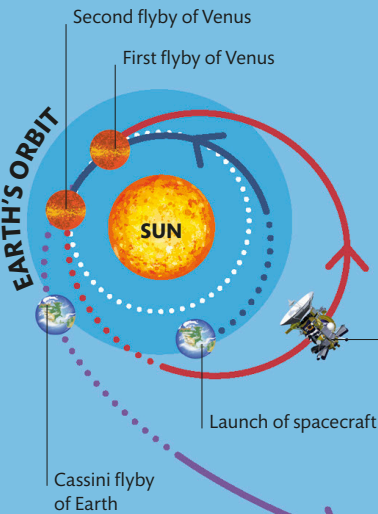


Voyage to Saturn

Putting a spacecraft in orbit around a planet requires a very different trajectory from a simple flyby. In order to approach Saturn at the correct angle, Cassini followed a seven-year flight path involving several gravity-assist manoeuvres.

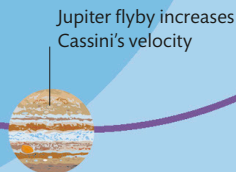
1 Venus assists

In 1998 and 1999, Cassini made two flybys of Venus. The first boosted its speed by 7 km (4 miles) per second, but it had to be slowed with an engine burn to put it on course for a second flyby and speed boost.



2 Return to Earth

In August 1999, Cassini flew past Earth at an altitude of 1,171 km (728 miles). The orbiter gained another speed boost of 5.5 km (3.4 miles) per second, putting it on the correct course for a flyby of Jupiter.

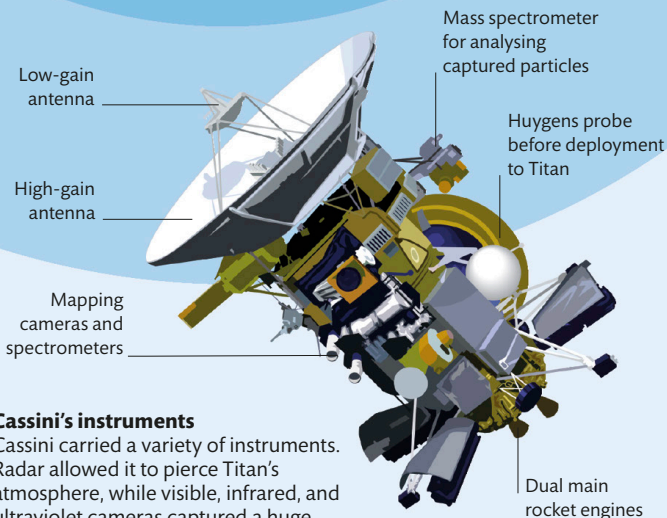


Jupiter flyby increases Cassini's velocity

JUPITER'S ORBIT

3 Jupiter swingby

In December 2000, Cassini flew past Jupiter at a distance of 9.7 million km (6 million miles). It conducted observations of the Solar System's largest planet and received a further boost to its speed.



Cassini's instruments

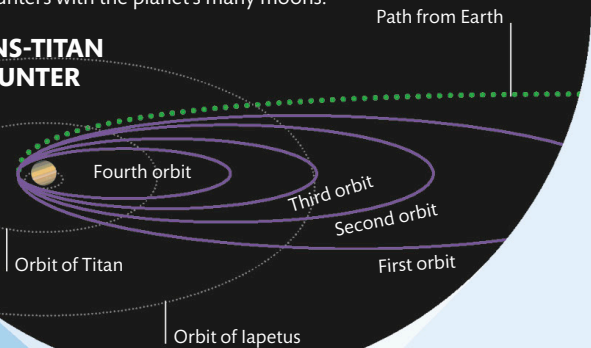
Cassini carried a variety of instruments. Radar allowed it to pierce Titan's atmosphere, while visible, infrared, and ultraviolet cameras captured a huge variety of information.

Orbiting Saturn

During Cassini's 13 years at Saturn, its orbit was repeatedly changed using gravity assists (mostly from Titan) and occasional engine burns to ensure close encounters with the planet's many moons.

HUYGENS-TITAN ENCOUNTER

SATURN



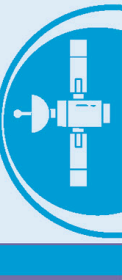
Spacecraft reaches Saturn's orbit

4 Arrival at Saturn

In mid-2004, Cassini successfully entered the Saturn system and used its main engine in two manoeuvres that shed speed and dropped it into an initial elliptical orbit of the planet.

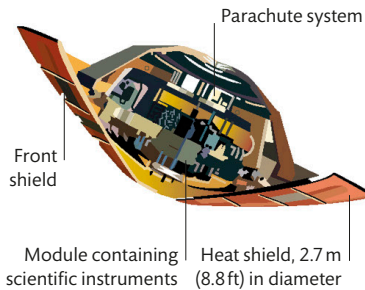
The Cassini orbiter

The bus-sized Cassini spacecraft remains the most complex uncrewed spacecraft sent into space by NASA. Launched in 1997, it orbited Saturn between 2004 and 2017, sending back a wealth of information about the planet, its rings, and its huge family of moons. The spacecraft also carried Huygens, a Titan lander built by the European Space Agency (ESA) that was released five months after Cassini's arrival in orbit. At the end of its mission, Cassini was crashed into Saturn's atmosphere to avoid possible contamination of its moons.



HUYGENS ON TITAN

The Huygens lander carried a variety of scientific instruments to investigate conditions on Titan. Uniquely, the probe was designed to float, since extensive lakes of liquid hydrocarbon chemicals were expected on Titan's surface.



HUYGENS PROBE

**GASES AROUND
THE GALILEO
PROBE REACHED
TEMPERATURES OF
15,500°C (28,000°F),
BURNING AWAY ITS
HEAT SHIELD**



HOW BIG WAS CASSINI?

The Cassini spacecraft was 6.8 m (22.3 ft) long and 4 m (13 ft) wide, with a mass of 2,150 kg (4,740 lb), plus 3,132 kg (6,905 lb) of rocket propellant.

Orbiting giants

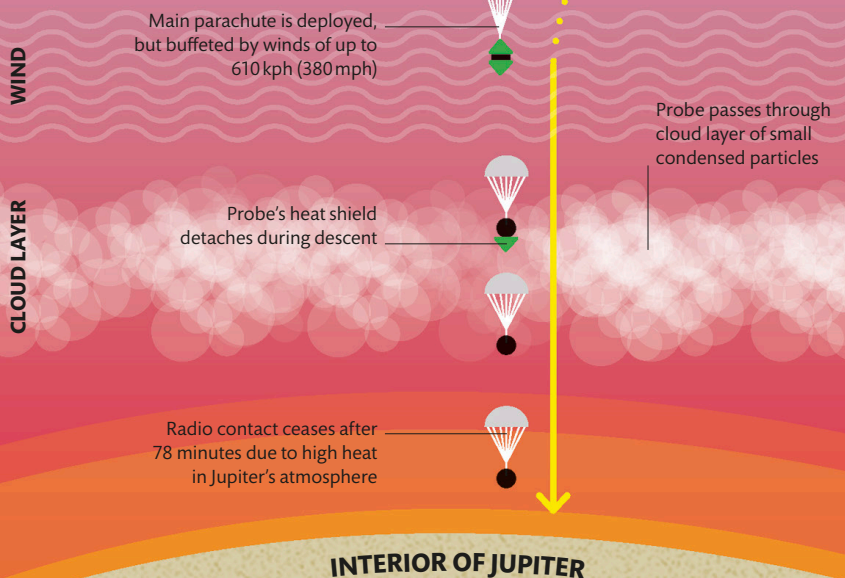
The Grand Tour flybys of the 1980s (see pp.210–11) were followed by more detailed explorations of the giant planets Jupiter and Saturn using complex spacecraft that remained in orbit for years.

The Galileo mission

The Galileo spacecraft orbited Jupiter from 1995 to 2003 and successfully carried out multiple flybys of the planet and its four giant satellites: Io, Europa, Ganymede, and Callisto (see pp.68–71). Galileo shed its excess speed without a retrorocket burn thanks to a daring aerobraking strategy in which it slowed down by dipping into the upper layers of Jupiter's atmosphere. Shortly after its arrival, the spacecraft deployed an atmospheric probe that parachuted into Jupiter's clouds and sent back valuable data about their composition.

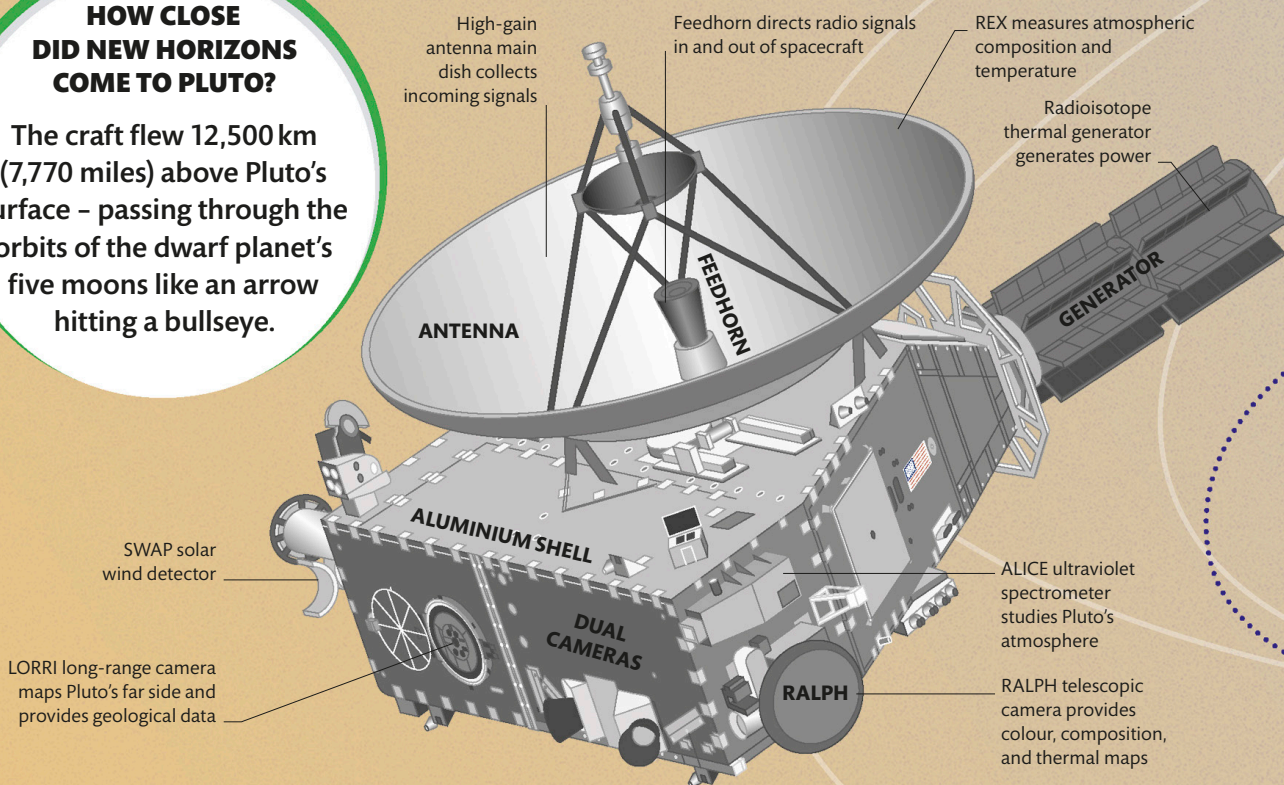
Probing Jupiter's atmosphere

Galileo's atmospheric probe entered Jupiter's gassy outer layers at a speed of around 48 km (30 miles) per second. In the space of two minutes, the probe slowed to subsonic speeds before deploying its parachute.



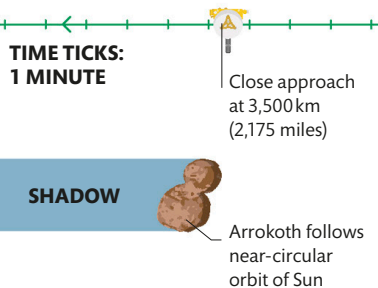
HOW CLOSE DID NEW HORIZONS COME TO PLUTO?

The craft flew 12,500 km (7,770 miles) above Pluto's surface – passing through the orbits of the dwarf planet's five moons like an arrow hitting a bullseye.



NEW HORIZONS' FLYBY

Following the encounter with Pluto, NASA was keen to send New Horizons to another Kuiper Belt object. Dwindling fuel limited their choices, but with a minor adjustment to the spacecraft's flight path, New Horizons was able to fly past and take images of a small world called Arrokoth on 1 January 2019.



Packing for Pluto

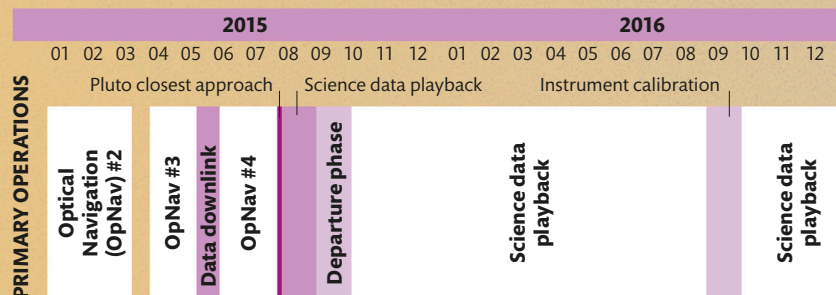
With the entire mass of New Horizons limited to 401 kg (884lb) plus propellant for its thrusters, the spacecraft had room for just 30 kg (67lb) of instruments. Power was also an issue, since the amount of fuel that could be carried to generate electricity was limited. Fortunately, scientists and engineers benefited from advances in microelectronics and were able to pack in seven separate instruments that operated on less than 28 watts in total.

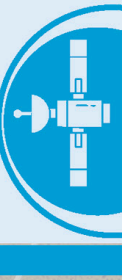
The path to Pluto

After leaving Earth, New Horizons flew past Jupiter a year later, receiving a gravity assist that boosted its speed. It then entered hibernation mode until late 2014, when it was awoken in preparation for the Pluto encounter.

Transmitting data

Sending radio signals from the edge of the Solar System is a challenge. With bandwidth needed during encounters for critical commands and navigation, New Horizons recorded its science data onto solid-state recorders, then sent it back to Earth over several months.





Gravity assist from Jupiter increases spacecraft's velocity, shortening voyage time by three years

In January 2006, New Horizons launches from Kennedy Space Center

SUN

JUPITER

Racing to Pluto

Despite no longer being classed as a major planet, Pluto is still among the largest objects in the Kuiper Belt (see pp.82–83) at the edge of our Solar System. In 2006, NASA launched New Horizons, a spacecraft that aimed to reach this dwarf planet while it remained relatively close to the Sun.

PLUTO ENCOUNTER

Orbit paths of Pluto's five moons

New Horizons' trajectory

New Horizons flew past Pluto at a speed of more than 84,000 kph (52,200 mph). The spacecraft took close-up images of Pluto, studied its atmosphere, and measured its mass.

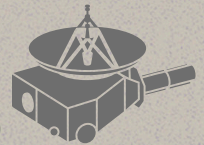
PLUTO

Flyby of Pluto in July 2015

Planning the mission

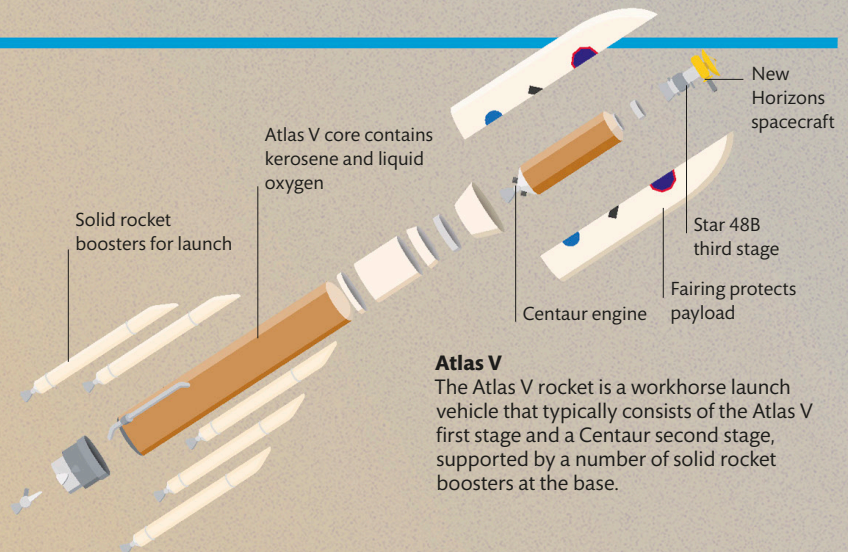
Pluto's elongated orbit means that its distance (and the ease of reaching it from Earth) varies significantly. Furthermore, conditions on the dwarf planet's surface were expected to change considerably depending on the amount of light reaching it from the Sun. Since Pluto was retreating from its closest approach to the Sun, which happened in 1989, time was of the essence – it was vital to keep the spacecraft light and fast.

NEW HORIZONS WAS THE FASTEST SPACECRAFT EVER LAUNCHED FROM EARTH, LEAVING ORBIT AT A SPEED OF 16 KM (10 MILES) PER SECOND



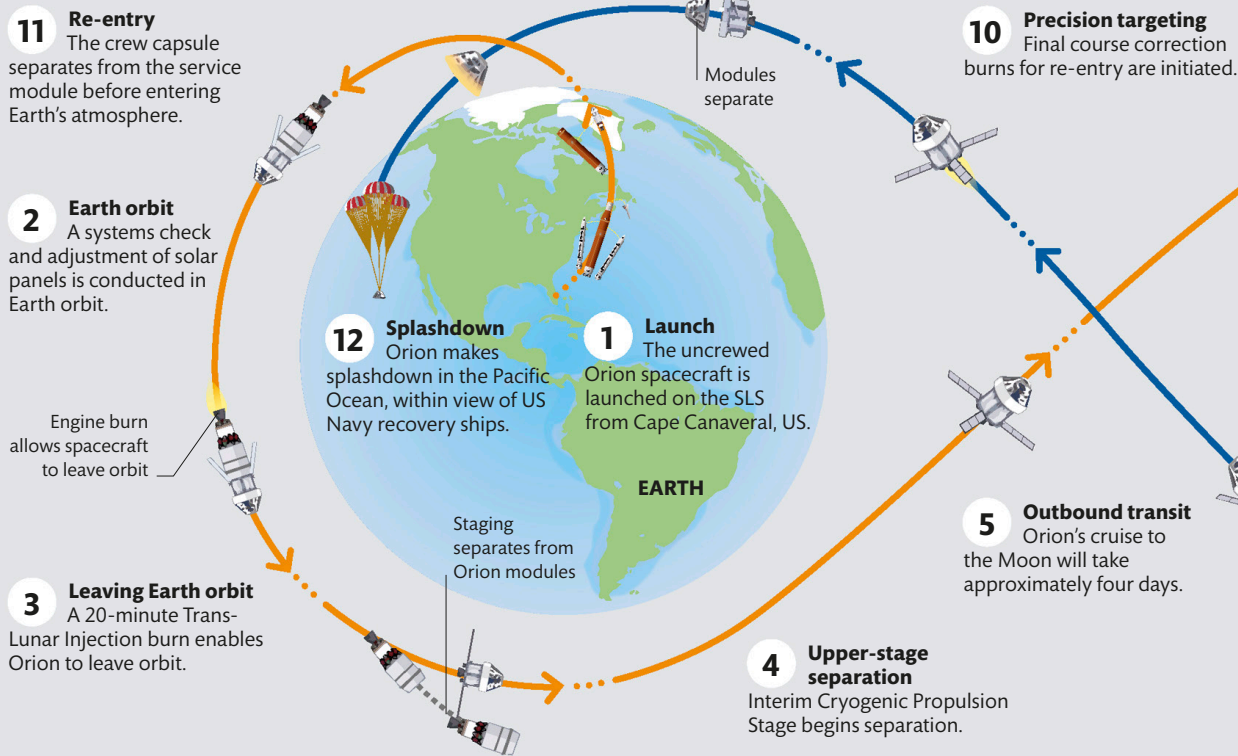
Launch boost

In order to send New Horizons on its way at high enough speed, the spacecraft was launched with a unique rocket configuration – a powerful Atlas 5b two-stage rocket assisted by an unprecedented five solid rocket boosters clustered at the base, and topped by a Star 48B third stage. This allowed the rocket to achieve, within just 45 minutes of launch, the speed necessary to escape the Solar System.



Atlas V

The Atlas V rocket is a workhorse launch vehicle that typically consists of the Atlas V first stage and a Centaur second stage, supported by a number of solid rocket boosters at the base.



Future spacecraft

In the near future, astronauts will travel in a variety of spacecraft, from commercial ferries running to and from the International Space Station (ISS), through suborbital capsules for space tourism, to advanced vehicles designed to explore the wider Solar System.

THE SLS BLOCK 2 VARIANT WILL LAUNCH 130 TONNES (143 TONS) TO EARTH ORBIT

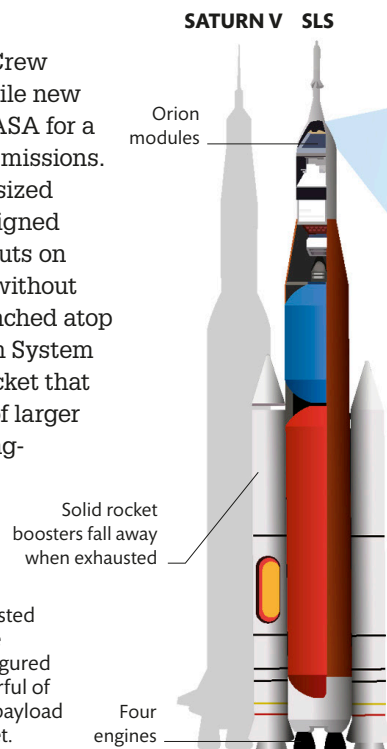


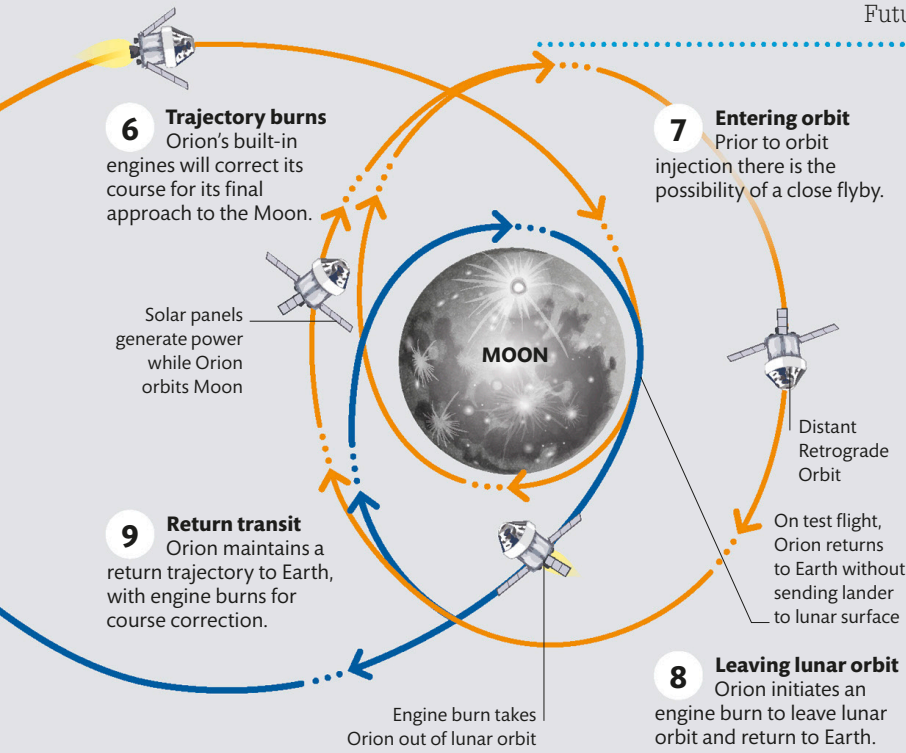
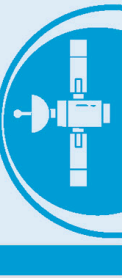
The Orion MPCV

The Orion Multi-Purpose Crew Vehicle (MPCV) is a versatile new spacecraft designed by NASA for a variety of new exploration missions. Looking a little like an outsized Apollo spacecraft, it is designed to carry four to six astronauts on missions of up to 21 days without support. Orion will be launched atop NASA's new Space Launch System (SLS) – a multi-purpose rocket that can also put components of larger spacecraft intended for long-duration interplanetary exploration into orbit.

Saturn successor

Initially derived from tried and tested elements of NASA's Space Shuttle programme, the SLS can be configured in various blocks, the most powerful of which can put 20 per cent more payload into orbit than the Saturn V rocket.



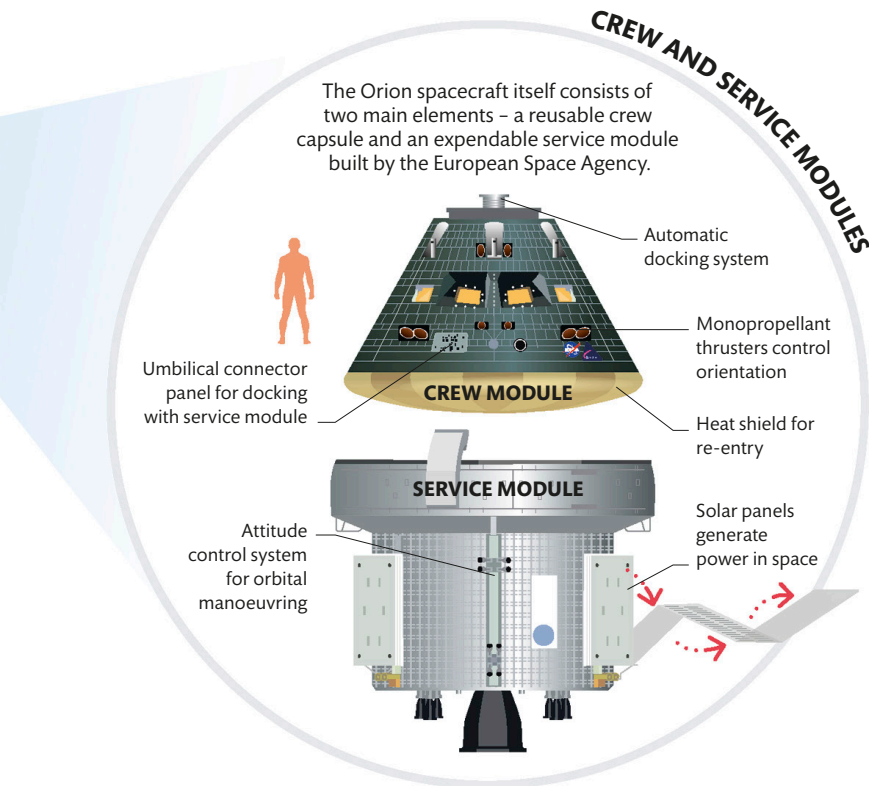


The future of Moon exploration

Orion and the SLS form the backbone of NASA's Artemis programme – an ambitious plan for a return to the Moon by around 2024. The programme involves establishment of a lunar gateway space station in orbit around the Moon, new cargo ferries to deliver supplies, and a new Human Landing System spacecraft to put men and women on the surface at the lunar south pole and support them for up to a week.

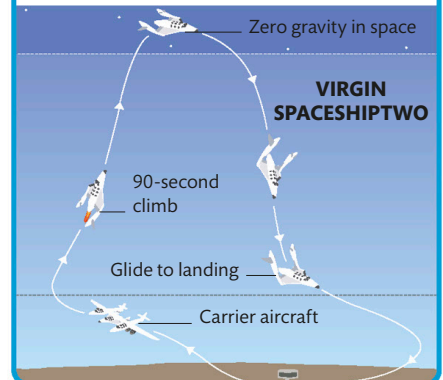
First step to the Moon

The initial Artemis 1 mission is an uncrewed flight to test key components of the SLS and Orion in Earth and lunar orbit.



SPACE TOURISM

The next decade will see various companies offering space tourism. Virgin Galactic's entry is the revolutionary SpaceShipTwo, a reusable, shuttle-like capsule that launches from a high-altitude carrier aircraft and powers to the edge of space using rockets before drifting back to Earth.



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